International Renewable Energy Agency

REACHING ZERO WITH RENEWABLES

BIOJET FUELS

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About IRENA

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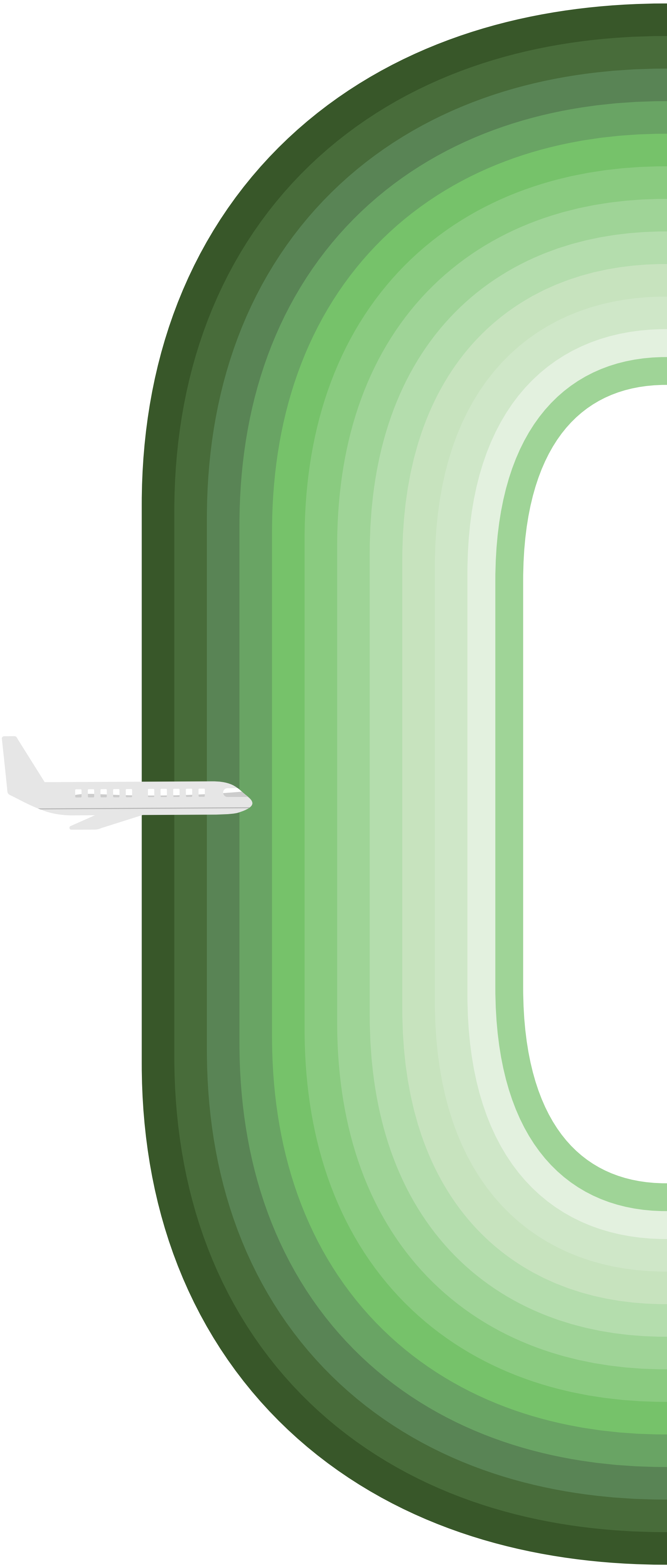

Eliminating emissions from industry and transport in line with the climate goal

SUMMARY FOR POLICY MAKERS

As part of society-wide global efforts to avoid the worst impacts of climate change, the aviation sector needs to make deep reductions in its carbon emissions by 2050. Although the sector will have to pursue multiple strategies, the large-scale production and use of aviation fuels derived from biomass (known as biojet fuels) will play a critical role in decarbonising the sector. This report summarises progress, explores the potential to scale up biojet production in the near and longer term, and explain the actions needed to realise the aviation sector's decarbonisation goals.

Context

- Globally, aviation produced 915 million tonnes of carbon dioxide (CO_2) in 2019 (2% of total global emissions). This is projected to double by 2050 in a business-as-usual scenario. Although the COVID-19 pandemic has affected the sector's emissions, the industry is likely to recover, reaching and exceeding pre-COVID emissions within a few years.
- The industry (through the International Air Transport Association [IATA] and the Air Transport Action Group [ATAG]) has committed to a 50% reduction in CO_2 emissions by 2050. This will be achieved with multiple approaches, including efficiency improvements, the use of sustainable aviation fuels (from biomass and

synthetic feedstocks), carbon offsetting and new technologies. Non-CO_2 emissions have a significant climate impact, contributing two-thirds of aviation's climate impact (Lee et al., 2021), but these are not currently addressed in official targets.

- With a growing number of countries committing to net-zero emissions targets for their economies by mid-century (over 30 countries to date including all G7 economies and the European Union), a 50% reduction may not be ambitious enough to achieve net zero, particularly if plans include a significant amount of offsetting.

- IRENA's 1.5°C Scenario (1.5-S), published in the World Energy Transition Outlook preview in March 2021, projects that aviation emissions will need to fall by about 90% by 2050. This is consistent with the goal of holding temperature rises to no more than 1.5°C above pre-industrial levels. The urgent timeline required for significant emission reductions means that any decrease in the carbon intensity of fuels needs to begin quickly and accelerate rapidly.

- Achieving deep emission reductions will require new technologies, including modifications to existing aircraft, new propulsion systems such as electric and hybrid aircraft (likely most suitable for small aircraft/short haul and a limited numbers of passengers), and the use of hydrogen (likely most suitable for short and medium haul and medium-sized aircraft). In addition, reduced demand for flying could also have an impact on emission reductions. Although the first commercial aircraft using alternative propulsion systems will soon become available, due to the relatively long life expectancy of aircraft (20-35 years) it will be several decades before these alternatives achieve large-scale penetration in the sector and lead to significant emission reductions.

- Prior to COVID-induced reductions, annual jet fuel consumption was about 360 billion litres/year. This was forecast to potentially more than double by 2050 (Galford, 2019; ICAO, 2019a; OPEC, 2020).

- To achieve early reductions in emissions during the 2020s and into the 2030s, plus deep reductions by 2050, the use of sustainable aviation fuels (i.e. fuels that have significantly reduced emissions compared to conventional jet fuel) will be essential. Biojet fuels are the most approved type of sustainable aviation fuel currently available, with many additional pathways under consideration. Synthetic jet fuel through the Power-to-X pathway may only in some cases fall within existing certified pathways and current production is highly limited due to high cost. Thus, biojet fuels hold the most promise for cost-effective scale-up and use in the coming decade.

Current biojet production

- Currently most biojet is produced via the hydrotreatment of fats, oils and greases (FOGs) such as used cooking oils. These oleochemical/lipid feedstocks are also known as HEFA (hydrotreated esters and fatty acids) or HVO (hydrotreated vegetable oils). Small volumes of alcohol-to-jet is currently available and this technology, as well as others such as gasification and Fischer-Tropsch synthesis, will provide greater volumes in the longer term.

- Current biojet production is about 140 million litres/year (2019), and although production has increased significantly (up from only 7 million litres in 2018), commercial volumes remain small (less than 1% of fuel currently used by the aviation sector). This is due to several factors such as the slow rate of technology development and the high cost of these fuels.

- Commercial production is currently limited to two plants that routinely supply nine airports. Biojet fuel is typically blended in low ratios with fossil jet fuel, although actual blending ratios are not known. Cumulatively, to date more than 315 000 flights have used a blend of biojet fuels.

- One of the added benefits of biojet fuels is that several technology pathways also produce lower-carbon-intensive diesel or gasoline fractions that can be used in other applications.

- To date, eight pathways have received ASTM[1] certification, which allows biojet fuel to be blended with petroleum-derived jet fuels or co-processed. The vast majority of biojet fuel currently produced and used in this way is derived from FOGs via the HEFA/HVO route.

- Fuels produced via the HEFA/HVO route cost three to six times more than conventional jet fuel, depending on the current cost of petroleum jet fuel and the lipid feedstock used to make the biojet. The price of HEFA as of September 2020 was USD 2 124/tonne based on the Argus Media index (Argusmedia, 2020), which amounts to approximately USD 272 per barrel or USD 1.7 per litre.

Scope for scaling up biojet production in the near term

- The biojet fraction is one component of the fuel output of HEFA/HVO biorefineries. It is currently more favourable for refineries to sell all liquid product as renewable diesel than to separate the biojet fraction from the renewable diesel (or advanced biodiesel), but changes in policies and incentives could address this to increase the volume of biojet available in the short term.

- With limited investment and with the right policy drivers in place, nearly all existing renewable diesel facilities could be incentivised to produce biojet as well as renewable diesel by fractionating the liquid product into two separate fuel products, jet and diesel. If all existing HEFA production facilities invested in additional infrastructure, such as reactors for isomerisation and fractionation, and put in place the processes to separate the biojet fraction, an additional 1 billion litres of biojet fuel could become available (approximately seven times current volumes).

- The maximum potential percentage of the biojet fraction could be increased from 15% to about 50%, but this would result in higher production costs due to greater processing and higher hydrogen demand, while also incurring a 10% loss of yield in liquid product (Pearlson, 2011).

- Beyond existing facilities, there is substantial scope for new or expanded production capacity to produce higher volumes of renewable diesel and biojet from waste FOGs. Many existing facilities are rapidly expanding to address a growing demand for renewable diesel. Many of these facilities could readily produce biojet as well.

- As the HEFA/HVO route to biojet is technically mature, the major challenge that has to be resolved is the high cost of feedstocks and sustainability. More sustainable, less carbon-intensive "waste" oils such as used cooking/tall oils are only available in limited quantities.

1 ASTM International is one of the largest voluntary standards developing organisations in the world. It develops technical documents that are the basis of manufacturing, management, procurement, codes and regulations for dozens of industry sectors (www.astm.org/ABOUT/faqs.html).

- Potential biojet production from estimated volumes of used cooking oil (UCO) is in the range of 3.5-12.0 billion litres globally, based on a 15-50% jet fraction from HEFA production. This is a conservative estimate and other reports have indicated that waste oils could supply up to 85 million tonnes (101 billion litres) of sustainable aviation fuel per year (McKinsey & Company, 2020a).

- To significantly scale up production, alternative feedstocks such as lignocellulosic biomass, and technologies such as gasification with Fischer-Tropsch and/or pyrolysis or hydrothermal liquefaction will be required.

- Other vegetable-derived oils such as soy, sunflower and canola/rapeseed are also used. Several studies have shown the relatively low carbon intensity and overall sustainability of these crops in specific cases, although these depend on specific agricultural practices and geographical location as part of a life cycle assessment. The relatively high cost of these feedstocks and ongoing concerns about diverting possible food crops has increased the interest in the commercialisation of technology pathways that use non-food biomass.

- Additional volumes of biojet could be derived from other biogenic feedstocks, such as forest and agricultural residues, sludge, algae and waste gases. Work by IRENA and others has indicated that this material could be supplied on an annual basis without adversely affecting the environment. However, actual utilisation of feedstock will depend on the cost, sustainability and competition with other applications. Supply chain innovation and optimisation will play a key role in future cost improvements.

Long-term prospects for biojet production

- In the future, due to the finite availability of lipid/oleochemical feedstocks, additional biojet technologies and feedstocks will be needed. These low-carbon-intensity fuels can be produced by processes such as gasification, pyrolysis, hydrothermal liquefaction and alcohol-to-jet.

- These “advanced” biojet fuels will be derived from more available biomass substrates such as agricultural, forestry and effluent wastes, and algae. Although it is likely that in the medium to longer term biojet fuel will be produced in high volumes via such technologies, the pathways need to be more fully commercialised and effective biomass supply chains established.

- In the short to medium term, the production cost of biojet fuels will be much higher than conventional jet fuel. This will be a major obstacle unless suitable policies are introduced. The high cost of feedstock is an obstacle for technologies such as HEFA, while high capital cost will be an obstacle for other technologies such as gasification.

- Over time, the price of biojet will decrease as multiple facilities come into operation. It is likely that learning will help enhance technology optimisation, as well as the establishment of optimised feedstock supply chains. Although it is not clear if, or when, biojet will reach price parity with conventional jet fuels, the pricing of carbon will play a significant role.

- Thus, policies will be essential to both create market demand and to further catalyse the development of biojet fuels. Although significant capital investment will be needed to establish more production facilities, technology push policies, in the form of grants and loan guarantees, will also help facilitate the construction and operation of these facilities.

Future levels of demand for biojet and cost

- There is high degree of uncertainty regarding the volume of biojet that will be required by 2050. It is dependent on global and national emission goals, the demand for aviation and the extent to which other technological and systemic options are adopted. However, given future projections and the technological and practical constraints of alternative, low-carbon-intensive propulsion systems, large volumes of biojet fuel and e-fuels (synthetic fuels) will be required if aviation is to meet the 2050 targets.

- The aviation sector's emission reduction target of 50% is likely to require in excess of 100 billion litres per year of available biojet by 2050. IRENA's 1.5°C Scenario (1.5-S) , which has a goal of holding the global temperature rise to no more than 1.5°C, estimates that about 200 billion litres per year of biojet fuel will be required. Although investment costs will vary significantly, depending on technologies, feedstocks and geographical locations, this is likely to involve around USD 5 billion of investment per year.

- The International Civil Aviation Organization (ICAO) carried out a study looking at complete replacement of conventional jet fuel in international aviation based on available feedstock and technology scenarios. Although required volumes will depend on growth in demand and the ability of other measures to reduce emissions, and are subject to significant uncertainty, the complete replacement of conventional jet fuel of 460-730 billion litres would require approximately 170 new large bio-refineries to be built every year from 2020 to 2050 (assuming a 50% biojet fraction) and investment of USD 15 billion to USD 60 billion per year (ICAO, 2019a).

- Currently biojet fuel is significantly more expensive than conventional jet fuel and is likely to be so for some time to come (for at least the next 5-10 years). Information of contract prices is not publicly available, but the actual market price paid in Rotterdam for HEFA sustainable aviation fuel in September 2020 was USD 2 124.47 per tonne (~USD 272/barrel of jet; USD 1.7/litre), amounting to 3-6 times the price for conventional jet fuel (Argusmedia, 2020).

- The HEFA-based production of biojet fuels is the only fully commercial technology for which fairly reliable and accurate cost information is available. Many of the techno-economic analyses of other "advanced" biojet fuel technologies have been based on modelling and unverified assumptions.

- Although the minimum fuel selling price of biojet fuels, as calculated in techno-economic analyses, is an important metric, it should not be considered in isolation of the broader "value" of the biojet. For example, the specific carbon intensity of the fuel will have an impact on the incentives available through policy measures.

- An alternative way of looking at cost is calculating the specific cost of carbon abatement, rather than just the minimum fuel selling price, as this takes into account the price of the fuel and the price relative to the emission reductions offered.

Policy actions required

- Delivering the levels of biojet production needed to achieve significant emission reductions is technically possible, although very challenging. It will require a supportive policy framework, both at the international (e.g. ICAO) and national level.

- As biojet fuels are, for the foreseeable future, likely to be more expensive than conventional jet fuel, innovative and stable policies will be needed to bridge the price gap between fossil-derived jet and biojet fuels.

- Current policies that have encouraged the production and use of lower-carbon-intensive transport fuels for road transport need to be adapted to allow lipid/biocrude-derived fuels with a low carbon intensity to be preferentially used for aviation.

- Volumetric biofuel mandates (e.g. bioethanol/biodiesel) do not generally consider the emission reduction potential of a fuel. Low-carbon fuel standards that consider the overall carbon intensity of a final fuel have proven effective in encouraging the supply, production and use of low-carbon-intensive transport fuels. Such policies set emission reduction targets rather than volumetric mandates and the actual volume may vary depending on the carbon intensity.

- Further policy elements, such as incorporation of a multiplier (e.g. x1.2) to allocate more "credits" to biojet fuels than renewable diesel, will be needed to address competition between the various low-carbon-intensive fuels.

- While volumetric mandates are being considered in various jurisdictions, there is some debate whether this is premature when biojet volumes are limited and based on only one technology.

- Policies such as a low-carbon fuel standard can also encourage the participation of the oil refining sector through the "repurposing" of refineries, as pioneered by companies such as World Energy and Neste to make predominantly renewable diesel, or via co-processing strategies, such as those adopted by some refineries belonging to BP and ENI.

- As well as market pull, policies should support "technology push", such as financial and policy support for research, development and demonstration, and all stages of the supply chain, including the development and scaling up of technologies, feedstocks, downstream logistics, sustainability assessment, etc.

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Abbreviations

1.5-S	1.5°C Scenario
APR	Aqueous phase reforming
ATAG	Air Transport Action Group
ATJ	Alcohol-to-jet
BtL	Biomass-to-liquids
CAAFI	Commercial Aviation Alternative Fuel Initiative
Cat. Hydro.	Catalytic hydrothermolysis
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
e-fuel	Electrofuel (synthetic fuel)
FOGs	Fats, oils and greases
FP	Fast pyrolysis
FPH	Fast pyrolysis and hydroprocessing
FRL	Fuel Readiness Level
FSRL	Feedstock Readiness Level
FT	Fischer-Tropsch
GtL	Gas-to-liquids
HEFA	Hydrotreated esters and fatty acids
HTL	Hydrothermal liquefaction
HVO	Hydrotreated vegetable oils
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
LCA	Life-cycle assessment
LCFS	Low-Carbon Fuel Standard
MFSP	Minimum fuel selling price
MSW	Municipal solid waste
NBC	Non-biogenic carbon
NPV	Net present value
PtL	Power-to-liquids
PtX	Power-to-X
RSB	Roundtable on Sustainable Biomaterials
SIP	Synthesised iso-paraffins
TRL	Technology readiness level
UCO	Used cooking oil

Units of measure

EJ	exajoule
g	gram
GJ	gigajoule
Gt	gigatonne
kg	kilogram
km	kilometre
kW	kilowatt
L	litre
MJ	megajoule
Mt	million tonnes
MWh	megawatt hour
yr	year

1. INTRODUCTION

Tackling climate change

Although we have made progress in decarbonising many aspects of the world's energy matrix, with solar, wind and hydro all adding to "green" electricity generation, long-distance transport has proven much more difficult to decarbonise. Increasing electrification of urban transport is anticipated, with a steady increase in hybrid and fully electrified cars. In contrast, long-distance transport, particularly aviation, marine and road freight, will be much harder to electrify. Similarly, other possible "green" options such as using renewable natural gas and green hydrogen, are proving challenging to commercialise and are likely to be at least a decade away.

The aviation sector contributes about 2% of the world's CO_2 emissions and about 12% of all transport emissions, amounting to 915 million tonnes (Mt) of CO_2 in 2019 (ATAG, 2020). Non-CO_2 emissions from aviation also have a significant climate impact, contributing almost two-thirds of net radiative forcing (Lee et al., 2021).

Until the impact of COVID-19 on the global economy, aviation was one of the fastest-growing transport sectors, with demand increasing at about 4% per year (Wheeler, 2018) and pre-COVID projections suggesting that the sector's emissions could grow to 2.1 gigatonnes (Gt) per year (IRENA, 2018).

Prior to the COVID pandemic, the International Air Transport Association (IATA) had set voluntary emission reduction targets that included improvements in fuel efficiency of 1.5% per year from 2009 to 2020, carbon-neutral growth from 2020 and a 50% reduction in emissions by 2050, based on 2005 levels (IATA, 2020a). As a result, multiple initiatives have been implemented, including improvements in airport and flight operations, innovative aircraft technologies and flight path changes (ICAO, 2019a).

In the past two years, a growing number of countries have committed to net-zero emissions targets for their economies by mid-century. As of early 2021, that included over 30 countries, including all G7 economies and the European Union. If global ambition is shifting to a net-zero goal, then a 50% reduction in aviation emissions will not be ambitious enough.

IRENA's 1.5°C Scenario (1.5-S), published in the World Energy Transition Outlook preview in March 2021, projects that aviation emissions will need to fall by circa 90% by 2050 as part of the pathway consistent with the goal of holding temperature rises to no more than 1.5°C (IRENA, 2021).

To add to the challenge, the trajectory for emission reductions is also critical, with reductions in all sectors needing to begin quickly and accelerate from there. And with all sectors seeking to decarbonise, the scope to offset emissions elsewhere will be limited.

Options for deep decarbonisation

Over the past ten years or so, since the aviation sector's original emission reduction objectives were agreed, progress has been made in decarbonising aircraft operations by improvements such as increasing the fuel efficiency of aircraft, new technologies to make aircraft lighter and modifying wingtips to reduce drag (ICAO, 2019a). For example, each new generation of aircraft is, on average, 20% more fuel efficient than the model it replaces (IATA, 2018). Additional emission reductions have also been achieved by modifying operations, such as renewable auxiliary power supplied by the airport, and upgrading navigation systems to optimise routing and reduce the amount of time in the air. The International Civil Aviation Organization (ICAO) also developed the first-ever global CO_2 certification standard for new aircraft in February 2017 (ICAO, 2017).

Ongoing improvements in fuel efficiency are anticipated; however, in the immediate future (1-5 years), carbon-neutral growth is only likely to be achieved through the purchase of offsets.

In the medium term, the options for deep decarbonisation are relatively limited. Aviation is dependent on high-energy-density fuels due to the mass and volume limitations of aircraft. With current aircraft designs, this limits the range of alternative fuels suitable for replacing jet fuel to some advanced biofuels and synthetic drop-in fuels (also known as e-fuels) (IRENA, 2020a).

Achieving deep emission reductions will require new technologies, including modifications to existing aircraft, as well as new propulsion systems such as electric and hybrid aircraft and the use of hydrogen. However, the time needed to develop and test such systems – together with the relatively slow pace of fleet replacement (the life-expectancy of aircraft is typically 20-35 years) – means that these new propulsion systems are unlikely to be seen in significant quantities until the 2040s.

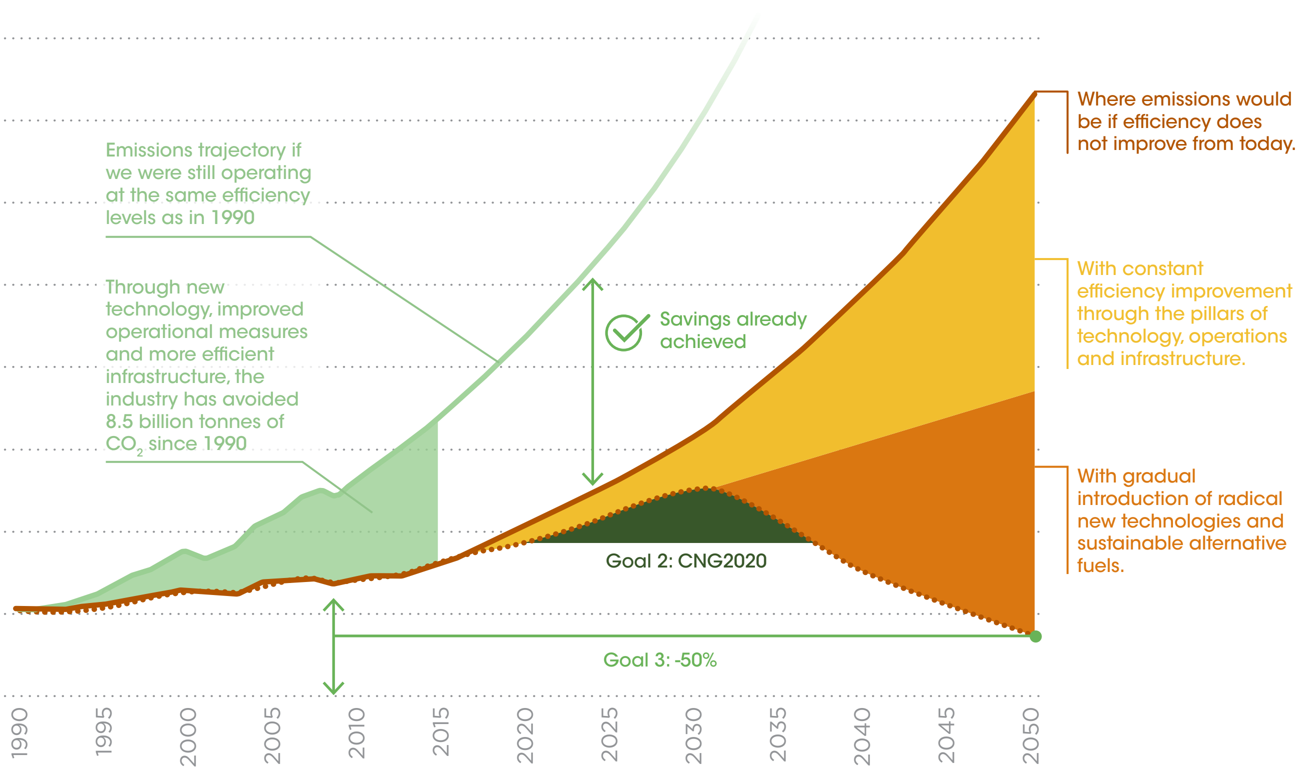
Electric propulsion has some advantages over jet engines, such as lower complexity and maintenance costs. However, due to technical limitations related to mass, weight and volume, the technology is currently only feasible for small planes and short-haul flights (IRENA, 2020a). When electric aircraft are commercially available, they are likely to be used for shorter flights involving smaller numbers of passengers. As 80% of aviation emissions are derived from flights of over 1 500 kilometres (km), the emission reduction impact of electric aircraft will be limited (ATAG, 2020). Hydrogen may be suitable for longer-haul and/or larger aircraft, but its potential remains unproven, and it is likely best suited to medium-sized aircraft and short- and medium-haul journeys.

To achieve early reductions in emissions in the 2020s and 2030s, and deep reductions by 2050, the use of sustainable aviation fuels[2] will therefore be essential.

Figure 1 illustrates the potential contribution of different options, although considerable uncertainties remain. Various factors such as decarbonising airport/land operations, increasing the efficiency of aircraft and new infrastructure investment will help reduce the sector's carbon emissions. Sustainable aviation fuels will provide the lion's share of the sector's decarbonisation potential (the orange section).

2 Sustainable aviation fuel is defined by ICAO as an alternative aviation fuel that meets certain sustainability criteria (www.icao.int/environmental-protection/GFAAF/Lists/FAQs/AllItems.aspx).

FIGURE 1. Schematic of the emissions reduction roadmap of the aviation industry according to the targets outlined



Source: ATAG (2017)

Sustainable aviation fuels

Biojet (i.e. aviation fuel produced from biomass) is currently the most certified type of sustainable aviation fuel. Over time synthetic aviation fuels produced from green hydrogen could also play a role as drop-in fuels, but production is currently very limited and costs are very high, exacerbated by a lack of demand for the fuels at the current price point (IRENA, 2020a). Biojet therefore holds the most promise for cost-effective scale-up and use in the 2020s and 2030s.

Currently there are several ways to make biojet fuels, with eight pathways already ASTM certified and several more in the pipeline. The current high demand for biojet fuels has resulted in several facilities being modified or reconfigured, as well as new facilities being built (Tuttle, 2020). However, as emphasised throughout this report, long-term, stable and ambitious policies are needed on an ongoing basis to catalyse significant growth in biojet fuel. Although biojet fuel-specific policies have been implemented in some jurisdictions, a more comprehensive, internationally relevant strategy is needed. The ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) – commencing in 2021 – aims to contribute to the sector's environmental objectives. However, in the short term it is debatable whether this will lead to a significant increase in biojet production and use, as it is likely that offsets will be cheaper than biojet fuels, allowing an airline to meet its obligations without the need to use biojet fuels (Pavlenko, Searle and Christensen, 2019).

2. PROJECTED BIOJET FUEL DEMAND TO 2050

The aviation sector contributes about 2% of the world's CO_2 emissions and about 12% of all transport emissions in 2019 (ATAG, 2020). Although not widely recognised, the vast majority of global transport energy needs are met by oil and petroleum products (96.7%), with biofuels (3.0%) and renewable electricity (0.3%) contributing only small amounts (REN21, 2020).

Before COVID affected global transport, various groups had projected global demand for all liquid transport fuels (primarily fossil-derived), including biofuels (IRENA, 2016a). It was anticipated that total biofuels would increase significantly from over 100 billion litres today to about 600 billion litres by 2050. IRENA's 1.5°C Scenario (1.5-S) , which has a goal of holding the global temperature rise to no more than 1.5°C, estimates that about 740 billion litres per year of liquid biofuels will be required, of which around 200 billion litres is biojet fuel (IRENA, 2021).

The consumption of jet fuel for commercial aviation in 2019 was approximately 360 billion litres. This volume also includes domestic flights as jet fuel consumption for international flights was only reported as being 160 billion litres in 2015 by ICAO (ICAO, 2019a). Due to COVID, consumption has dropped significantly and the industry is only expected to return to normal volumes of traffic by 2023-2024. Recent forecasts estimate that jet fuel demand for commercial aviation will double by 2050 (Galford, 2019; ICAO, 2019a; OPEC, 2020).[3] Actual fuel demand will depend on the effect of new technologies and improvements, and associated uncertainties. ICAO set a target of 2% improvement in fuel efficiency per year, although it seems unlikely to be met (ICAO, 2019a).

According to ICAO, international aviation emissions in 2015 were 506 Mt CO_2 and expected to be 655-713 Mt CO_2 by 2025. By 2050 emissions could reach a range of 1.2-1.9 Gt CO_2. ICAO assessed replacing 100% of jet fuel demand for international flights by 2050 (454-720 billion litres), but it would require significant scaling up over time – building approximately 170 large new bio-refineries every year from 2020 to 2050

3 ICAO : 454-720 billion litres by 2050 for international aviation;
US EIA : 832 billion litres by 2050;
OPEC World Oil Outlook : 546 billion litres by 2045.

– to reach a 63% reduction in life-cycle emissions, as different pathways achieve different emission reductions (ICAO, 2019a).

According to analysis by Staples et al., 850.3 Mt (955 billion litres) annual production of biojet can be achieved by 2050 if 178.7 exajoules per year (EJ/yr) of feedstock is available, and all that feedstock is first used for jet production before it is allocated to bioenergy and other applications. On this basis, a reduction in life-cycle emissions of about 68% can be achieved (Staples et al., 2018) . However, this scenario is merely theoretical and it is highly unlikely that feedstocks will initially be diverted to biojet fuel production.

It should be noted that actual life-cycle emission reductions from biojet will vary according to the feedstock and technology pathway. Reductions are also achievable with new technologies, modifications to existing aircraft, improved efficiency and purchase of offsets. The greater the emission reductions achieved through these pathways, the lower the volumes of biojet required to meet the climate objectives.

Current progress on biojet fuel production and consumption

Of the various drop-in biofuels that are currently produced, renewable diesel constitutes, by far, the largest volume. The vast majority of the world's renewable diesel is produced by hydrotreating oleochemical/lipid feedstocks. The production of oleochemical-derived "conventional" (i.e. lipid-derived) drop-in biofuels will initially deliver most biojet until "advanced" drop-in biofuels based on lignocellulosic biomass become commercially available. These biomass feedstocks have greater potential to be deployed in larger quantities at lower cost.

The established hydrotreated vegetable oils (HVO)/hydrotreated esters and fatty acids (HEFA) oleochemical route is currently also the major process used to make biojet fuels as a co-product with renewable diesel. However, production currently only takes place at Neste and World Energy, as it is economically more favourable to produce renewable diesel only. Renewable diesel is produced at a rate of more than 6 billion litres annually. Ongoing expansion of capacity is underway via the conversion or repurposing of existing, underutilised refinery infrastructure to renewable diesel production at a lower investment cost than construction of a greenfield facility. Current facilities include ENI (Italy), Total La Mède (France), Andeavour (North Dakota) and Phillips 66 (Rodeo, California).

As summarised in Table 1, although the number of renewable diesel facilities continues to grow globally, only two facilities produced biojet fuel in 2019, Neste (Rotterdam) and World Energy (California). The Neste Singapore facility is currently undergoing infrastructure modifications to produce biojet on a routine basis by 2022. It should be noted that only about 15% by volume of the total capacity of these refineries can be fractionated to produce biojet. Although this fraction can be increased (up to a maximum of 50%), it comes at a higher cost[4] and a loss of yield. At this point in time it is not economically attractive for companies to produce a higher biojet fraction (UOP, 2020).

4 Pearlson (2011) indicated that increasing the biojet fraction to 50% results in an increase of USD 0.25-0.30 per US gallon or USD 0.07-0.08 per litre.

TABLE 1. List of companies producing HEFA fuels (mainly renewable diesel)

Company	Location	Feedstock	Capacity (L/yr)
Neste	Rotterdam	Vegetable oil, UCO and animal fat	1.3 billion
	Singapore	Vegetable oil, UCO and animal fat	1.3 billion
	Porvoo, Finland	Vegetable oil, UCO and animal fat	385 million
	Porvoo 2, Finland	Vegetable oil, UCO and animal fat	385 million
ENI	Venice and Gela, Italy	Vegetable oils, UCO and animal fat	1 billion
Diamond Green Diesel	Norco, Louisiana	Vegetable oils, animal fats and UCO	1 billion
UPM	Lappeenranta, Finland	Crude tall oil	120 million
World Energy (AltAir)	Paramount, California	Non-edible oils and waste	150 million
Renewable Energy Group	Geismar, Louisiana	High and low free fatty acid feedstocks	284 million
Total	La Mède	UCO and vegetable oils	641 million
TOTAL CAPACITY			6.56 billion (±0.98 billion potential biojet at 15% by volume, ±3.28 billion potential at technical maximum)

Note: UCO = used cooking oil.

Source: Van Dyk et al. (2019a).

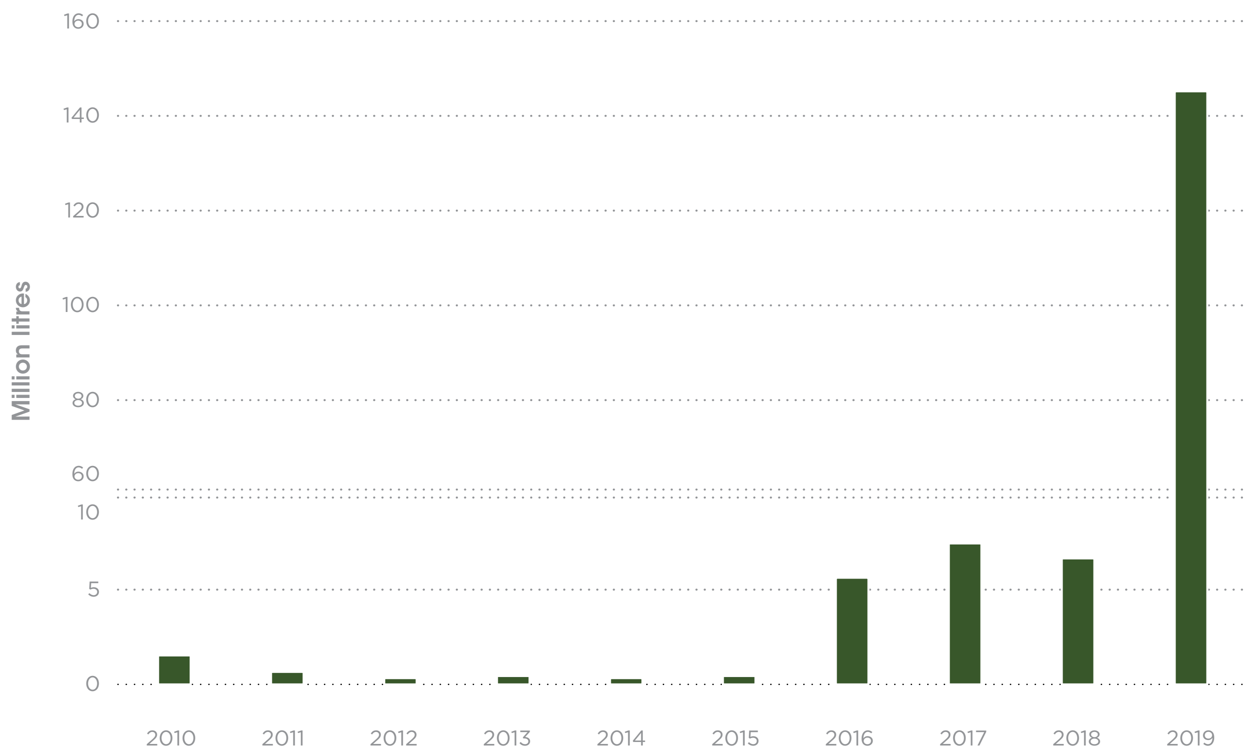
To date, over 315 000 commercial flights have used a blend of biojet fuel, with nine airports regularly distributing blended biojet fuel and another 13 airports supplying “batches” of biojet fuel blends (ICAO, 2020a).

As indicated in Figure 2, the amount of biojet fuel produced has increased substantially since 2007, with volumes jumping to about 140 million litres in 2019. This increase is attributed to Neste producing 125 million litres in 2019, whereas previous years’ data was mainly based on the production from World Energy.

Neste expects to produce about 1.25 billion litres of biojet per year by 2022 (Neste, 2020a). Although World Energy is reported to have invested USD 350 million to expand its Paramount facility from 150 million litres to about 1.135 billion litres (World Energy, 2020), it is not clear when this additional capacity will become available. However, it should be noted that only about 15% of this additional capacity will be biojet fuel.

As mentioned earlier, all the drop-in biofuels that have been produced to date, including the biojet fraction, have been derived using the “conventional” approach of hydrotreating oleochemical/lipid feedstocks. Although this pathway will continue to produce the bulk of biojet fuel over the next 5-10 years, feedstock availability is likely to become a limiting factor. In the longer term (over 10 years), it is expected that “advanced” biojet fuels, derived from agricultural and forest residues and other waste carbon feedstocks (including waste gases and carbon capture), will produce additional volumes of biojet fuels as these technologies are commercialised.

FIGURE 2. Biojet fuel production volumes, 2010-2019



Source: IRENA analysis based on Dickson (2019).

The "advanced" biojet fuel facilities that are currently under construction include Red Rock Biofuels, with an expected 56 million litre total capacity, and Fulcrum Bioenergy, with a projected 40 million litre total capacity. However, as these facilities are based on biomass gasification and Fischer-Tropsch (FT) synthesis, a fuel maximum of 40% jet fraction is estimated with current commercial technology. Other routes to advanced biojet fuel include alcohol-to-jet (ATJ), with Gevo making biojet fuel from isobutanol derived from corn, while LanzaJet[5] uses fermentation of waste carbon gases or syngas to make ethanol for the ATJ process (LanzaTech, 2020).

Theoretically, a biojet fuel component could be produced at any renewable diesel refinery. However, biojet production requires an additional fractionation step and, potentially, further processing such as isomerisation to ensure that ASTM specifications are met. As most renewable diesel facilities do not include these additional steps, World Energy Paramount was, until fairly recently, the only renewable diesel facility that produced biojet by fractionation. However, more recently, companies such as Neste have produced a biojet fraction after investing in the additional processing steps needed to supplement their renewable diesel facility (Neste, 2020b).

5 Production expected by 2022.

In summary, most "conventional" renewable diesel facilities can readily add infrastructure to produce biojet fuel as part of their product slate, as about 15% of the total liquid fuel produced will constitute biojet. Although the amount of biojet fuel can be increased, it decreases the overall yield. Thus, without specific policy drivers it would be economically unattractive. It is worth noting that if all of the world's current renewable diesel facilities were "encouraged", through policy drivers, to produce biojet fuel, approximately 1 billion litres per year could become immediately available at a limited investment cost. Based on current and planned facilities, ICAO estimates total refinery capacity by 2032 of 8 billion litres, with actual biojet production of between 1 billion litres (low ratio) and 6.3 billion litres (high ratio) anticipated (Dickson, 2019).

The impact of COVID-19 on the aviation sector's plans to decarbonise

The COVID-19 pandemic has had a dramatic effect on the aviation sector, with a total estimated reduction in passengers of at least 51-52% for 2020 (ICAO, 2020b). It has been projected by some groups that the world's airlines will lose about USD 84 billion in 2020, with more recent projections even more pessimistic, anticipating losses of USD 388-400 billion for 2020 (IATA, 2020b). Recovery back to 2019 levels is only expected by 2024 (Eurocontrol, 2020).

It has also proven challenging for airlines to reduce fixed and operational costs, with ongoing health measures resulting in higher operational costs even if there is a slow but steady recovery. Thus, it is highly likely that ongoing disruption will affect the sector's ambitious decarbonisation goals. While many of the world's airlines have received government aid to try to lessen the impact of COVID-19, various environmental groups have argued that these "bailouts" should be linked to climate mitigation efforts (Climate Change News, 2020). For example, the EUR 7 billion in government aid to Air France came with the conditions that:

"the airline cut its carbon intensity by 10% by 2030, halve the CO_2 emissions of flights within mainland France and use at least 2% alternative jet fuel by 2025."

(Climate Change News, 2020)

Cuts in domestic flight emissions include a reduction in domestic flights over distances where alternative ground transport is available. Although several other governments have also financially helped their national airlines, fewer environmental "strings" have been attached (Transport & Environment, 2020).

As discussed elsewhere in this report, the recent changes to the CORSIA baseline suggest that the pandemic might not play a significant role in influencing the sector's environmental aspirations. But it is likely that the aviation sector's ongoing challenges will make these goals even more problematic.

3. ALTERNATIVE PROPULSION SYSTEMS

AS A WAY OF MITIGATING EMISSIONS

In the future, electric and hydrogen-powered aircraft will help reduce the sector's CO_2 emissions as well as providing additional environmental benefits such as decreasing contrail emissions, improving local air quality and reducing noise pollution (ICAO, 2019a). However, emission reduction calculations must be based on a full life-cycle assessment, not just tailpipe emissions. For example, overall emission reductions will only occur if the source of electricity or hydrogen is from a renewable resource such as using solar/wind/hydroelectricity to recharge batteries or using "green" hydrogen to power a fuel cell.

Although there is enormous potential in these alternative propulsion systems, as mentioned earlier, most carbon emissions occur during long-distance flights while transporting large numbers of passengers. As aircraft have an average operating lifespan of about 30 years, and as it typically takes years to design and build these new propulsion systems, fleet replacement will not happen soon. It is likely that challenges such as the weight and size of batteries and sourcing green hydrogen will result in these technologies first being pioneered in short-distance flights involving a small number of passengers. Thus, any alternative propulsion systems used in long-distance flights are unlikely to have a significant impact on emission reductions before 2050 (Baraniuk, 2020).

Electric and hybrid aircraft

Electrically assisted propulsion involves the use of electric motors to drive some or all of the propulsion on an aircraft. Typically, propulsion relies on electric energy storage (e.g. batteries), hybrid energy (e.g. a mix of electric and fuel-based propulsion) or turboelectric (e.g. fuel-based energy) (Jansen et al., 2019). Electric aircraft are already being assessed for their potential over short distances, such as vertical take-off and landing, for urban transport or for short distances over mountainous terrain (Fairs, 2019). However, as pioneered in the automotive sector, it is likely that hybrids will be the first to be commercialised, combining current jet engine technology with a battery electric source. For example, hybrid aircraft will use electricity for some of their propulsion, e.g. for taxiing or for take-off to provide additional thrust, while predominantly using fuel-based propulsion to achieve cruising. The world's first fully commercial electric aircraft took off in Vancouver in December 2019 with a claimed range of 160 km (The Guardian, 2019). However, a significant challenge for electric aircraft is the energy density of the batteries, which is about 40 times less than the same weight of jet fuel (Ros, 2017).

Currently, ICAO maintains a non-exhaustive list of "Electric and Hybrid Aircraft Platforms for Innovation" (E-HAPI) on its website (ICAO, 2020c). Potential applications have been categorised into four groups:

- "The general aviation/recreational aircraft group consists of aircraft with a maximum take-off weight between 300 kilogrammes (kg) and 1000 kg. These are mostly electrically powered aircraft with a seating capacity of two. This category includes aircraft that are already produced and certified.
- Aircraft under the business and regional aircraft category can achieve longer flights, close to 1000 km, with increased seating capacity (around ten).
- The large commercial aircraft category includes initiatives focused on hybrid-electric, single-aisle aircraft with seating capacities of 100-135 and targeted entry into service after 2030.
- Aircraft with vertical take-off and landing capability have a seating capacity from one to five, a maximum take-off weight between 450 kg and 2 200 kg, and a projected flight range of 16 km to 300 km. These aircraft are electrically powered with a goal of entering service during 2020-2025. Significant progress has also been made in this category.

Hydrogen-powered aircraft

Aircraft can use hydrogen either as a fuel for a jet engine or to supply a fuel cell that can provide electricity for propulsion (Baroutaji et al., 2019). When used as a fuel, hydrogen must be compressed or stored as a cryogenic liquid, with safe storage and refuelling recognised as critical steps. To date, most hydrogen is produced via the steam reforming of natural gas with only limited amounts of renewably sourced (green) hydrogen currently available. If green hydrogen is to contribute to decarbonising the aviation sector, its production will have to be scaled up dramatically (O'Callaghan, 2020). "Blue" hydrogen can provide a lower carbon intensity via the capture and storage of carbon emissions at the site of production. Airbus recently announced a target of enabling the "first climate-neutral, zero-emissions commercial airplanes up to cruising altitude within the next 15 years". They suggest that two types of aircraft will be available by this time: a 200-passenger aircraft that can fly up to 3 700 km or 2 000 nautical miles, and a 100-passenger aircraft that can fly up to 1850 km or 1000 nautical miles (Nelson, 2020). Although these aircraft will be powered by hydrogen, the actual emissions will depend on the source of the hydrogen and its production as assessed over the entire life cycle of the hydrogen production pathway. A recent report from the European Commission, as part of the Clean Sky project, indicated that hydrogen propulsion could play a significant role in the future. However, the report also stated that "it will require significant research and development, investments and accompanying regulation to ensure safe, economic H_2 aircraft" (McKinsey & Company, 2020b). It was also concluded that, "although hydrogen-powered aircraft can contribute to emission reductions, it is best suited for 'commuter, regional, short-range, and medium-range aircraft' with long-range flights powered by hydrogen likely proving more challenging" (McKinsey & Company, 2020b). In addition, significant, safe hydrogen refuelling infrastructure has yet to be developed at airports.

By contrast, drop-in biofuels such as biojet fuels can be used in the same infrastructure, including fuel tanks, pipelines and jet engines. Depending on the source of the biojet fuel, emission reductions of close to 100% are possible.

4. BIOMASS FEEDSTOCK AVAILABILITY

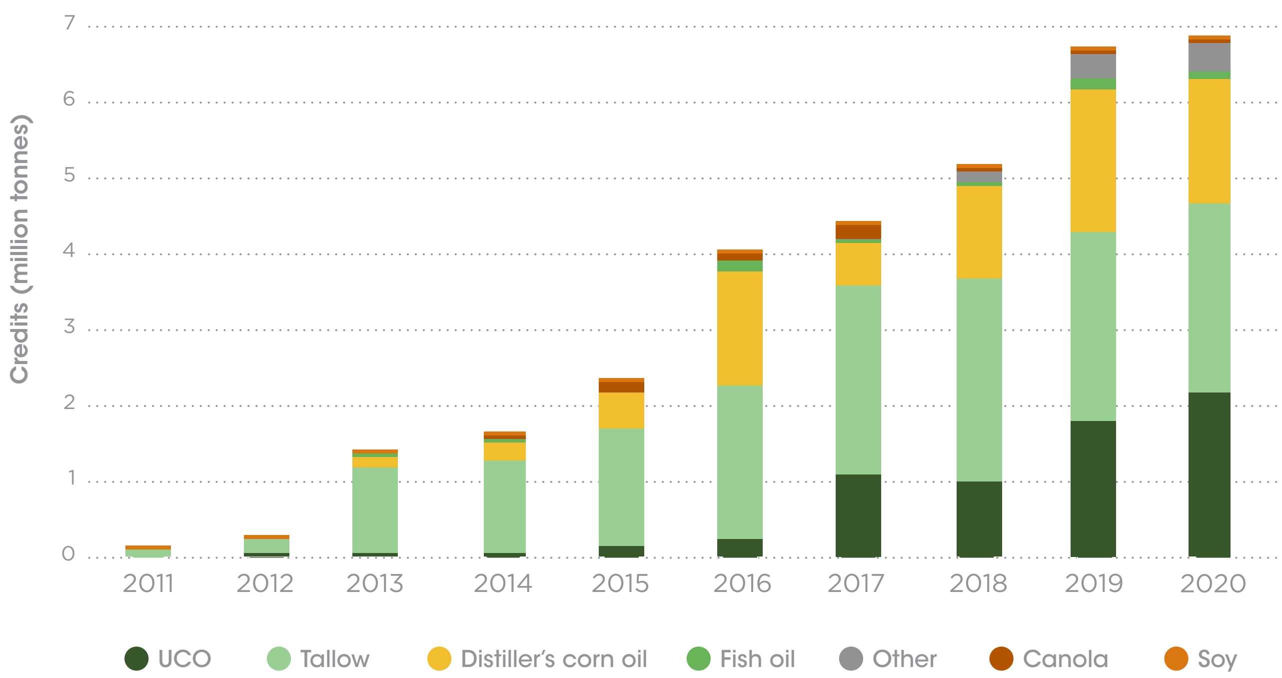
The two main feedstock categories that are primarily being pursued are the oleochemical/lipid-based processes (using fats, oils and greases [FOGs], vegetable oils and animal/rendered fats) and the so-called biocrude-based processes derived from various lignocellulosic/biomass feedstocks (such as agricultural residues and woody biomass).

The vast majority of biojet fuel that is produced today is derived via the oleochemical/lipid "conventional" route, and this conventional route to biojet fuels is likely to dominate the biojet market in the coming decade.

As demonstrated by companies such as Neste, lipids are a relatively high-density feedstock, which allows them to be more readily transported over long distances, achieving benefits such as larger economies of scale. For example, the Neste facilities in Rotterdam and Singapore produce over one billion litres of renewable diesel per year, partly as a result of the company successfully establishing a global supply chain, sourcing fats and oils from New Zealand, Australia, China, Canada and other countries. Currently, alternative crops such as camelina, carinata and salicornia are also being assessed as lipid feedstocks for potential biojet fuel production. However, further work is required to fully develop and optimise these supply chains, including the establishment of more routine processing infrastructure.

As the technology used to make conventional biojet is relatively mature, the amount, cost and overall sustainability of the feedstock will be very important. For example, structuring policies to link with the carbon intensity of fuels in California has encouraged the increased use of waste lipid feedstocks such as used cooking oil and tallow (Figure 3), and this is reflected in the current feedstock mix used by companies such as Neste (Figure 4). One of the critical aspects of sustainability is the need for overall emission reductions, with CORSIA requiring at least a 10% reduction across the entire supply chain (ICAO, 2019b).

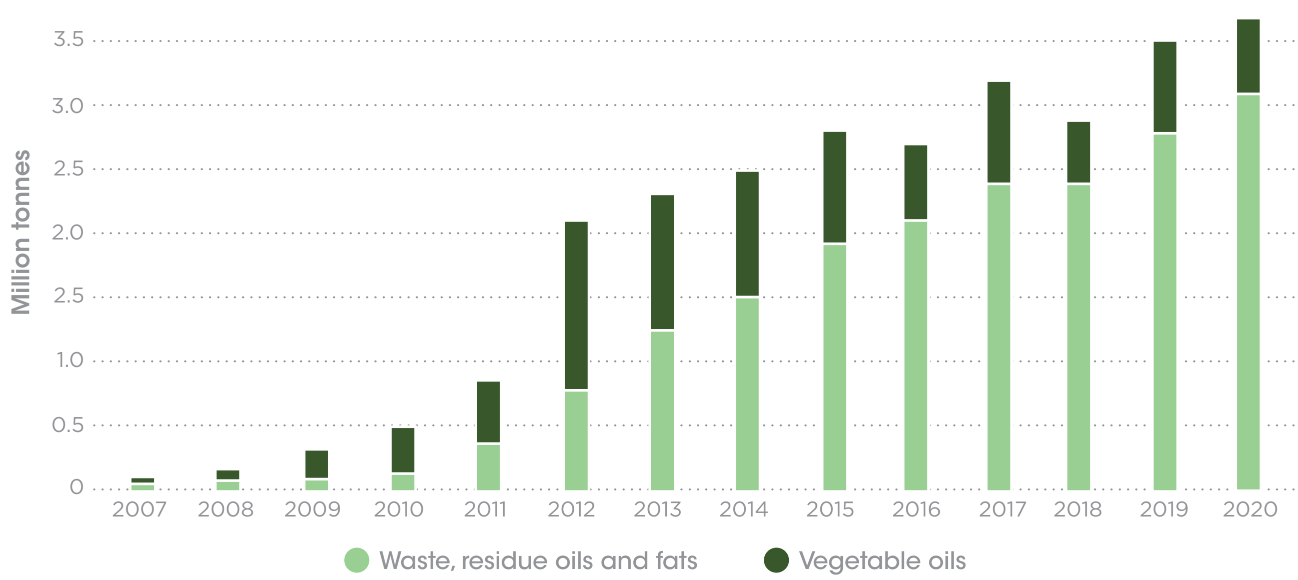
FIGURE 3. Utilisation of waste and residue oleochemical feedstocks in California as represented by LCFS credits, 2011-2020



Notes: LCFS = Low Carbon Fuel Standard. The LCFS incentivises the use of biofuels derived from waste feedstocks. From 2018, 98% of the total carbon credits generated by biodiesel and renewable diesel were derived from wastes and residues rather than crop-based oleochemicals/virgin vegetable oils.

Source: CARB (2019).

FIGURE 4. The change in feedstocks used by Neste to produce renewable diesel, 2007-2020



Notes: Both LCFS-type policies and the sustainability compliance requirements in biofuel policies have encouraged biofuel producers to use waste/residual raw materials.

Source: Neste (2019, 2021).

In contrast, advanced biojet fuel based on biomass (biocrudes), waste carbon, alcohols and sugars is still very much under development. As described earlier, lignocellulosic materials, such as agricultural residues and woody biomass, will be the primary feedstocks for thermochemical technologies such as gasification and thermochemical liquefaction (pyrolysis, etc.) (Karatzos et al., 2017). In addition, biomass feedstocks can be used to produce sugars that may be fermented to alcohols for ATJ production, or directly fermented to hydrocarbons such as farnesene (Karatzos, Mcmillan and Saddler, 2014).

A key characteristic of biomass feedstocks is their low energy density, which makes their transport over long distances (more than 100 km) economically challenging (Lin et al., 2016; Miao et al., 2011). As a result, densification to pellets or liquid intermediates such as biocrudes are likely to be needed to make transport more attractive. However, this will increase the cost of the feedstock. As supply chains are already in place for pellet-fired bioenergy applications such as heat and electricity generation, this infrastructure could be readily adapted for potential biofuel facilities such as a thermochemically based biojet fuel plant (Boukherroub, LeBel and Lemieux, 2017). With the ongoing need for sustainably sourced biomass pellets, producers are increasingly sourcing forests residues to supplement the sawmill residues that still predominate as pellet feedstocks (Larock, 2018). However, the quality of these feedstocks in terms of moisture content, homogeneity, etc., can negatively affect the biocrude/bio-oil products and eventual drop-in biofuel production.

Agriculture-derived residues could potentially supply considerable quantities of biomass for biojet fuel production. However, supply chains are not well-established and the operational challenges encountered by the various cellulosic ethanol plants highlight the complexity of collecting, storing and utilising agriculture residues for biofuel production (Gold and Seuring, 2011). Although municipal solid waste (MSW) and other waste sources can potentially be used as low-cost feedstock, as demonstrated by companies such as Enerkem,[6] these feedstocks are generally of poor quality and extensive pretreatment is typically required before they can be used (Shahabuddin et al., 2020).

Despite these challenges, meeting the long-term need for biojet fuels assumes that sufficient feedstock will be available from sustainable sources for advanced routes to biojet fuels. Although somewhat in the future, ICAO has indicated that advanced, biomass-derived biojet fuels should be able to meet CORSIA's sustainability guidelines with the proviso that:

> *"CORSIA eligible fuels are not to be made from biomass obtained from land with a high carbon stock. CORSIA eligible fuel shall also not be made from biomass obtained from land converted after 1 January 2008 that was primary forest, wetlands, or peatlands and/or contributes to the degradation of the carbon stock in primary forests, wetlands, or peatlands as these lands all have high carbon stocks."*
>
> *(ICAO, 2019c)*

All in all, the availability, cost and overall sustainability of biojet fuel feedstocks will be of ongoing concern, with the technically mature "conventional" route requiring a significant reduction in feedstock costs while the biomass-based "advanced" technologies are still in development and not yet commercial.

6 www.enerkem.com.

Feedstock readiness level to assess the maturity of potential feedstock supply chains

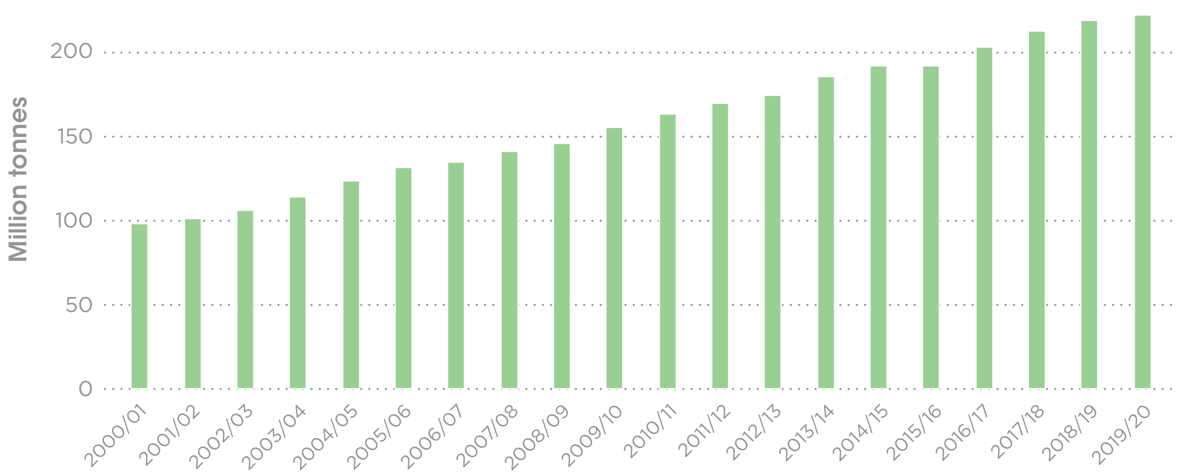
While the commercial readiness of a particular technology is often emphasised, the maturity of the feedstock supply chain is also important. The Commercial Aviation Alternative Fuel Initiative (CAAFI) has developed both a Fuel Readiness Level (FRL) and a Feedstock Readiness Level (FSRL) evaluation to separately measure the status of both parts of the supply chain. The FSRL assessment is based on a number of factors, including:

- production (growing and harvesting of feedstock)
- market readiness (logistics and infrastructure for movement from harvest to bioconversion and commercial market availability)
- policy/regulatory compliance (factors that promote or discourage the production of a feedstock)
- linkage with a biofuel conversion process (whether the feedstock matches the quality and quantity demands of the biofuel producer).

All these factors need to be addressed when considering a new feedstock for biojet fuel production, as do other aspects related to feedstock, region and stage of development of the biofuels industry (Steiner et al., 2012).

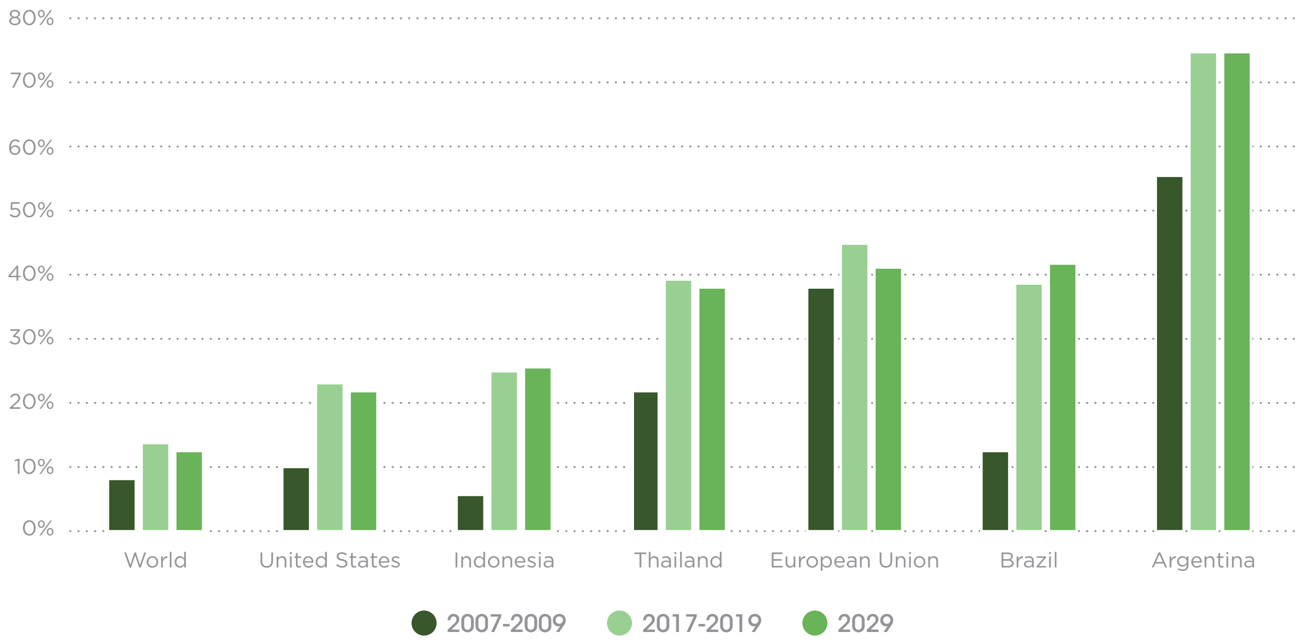
While companies such as Neste have shown that FOGs are available at a global level, quantities are finite. Although vegetable oils are much more available, they are mostly used for food purposes. Despite global vegetable oil production increasing to about 223 million tonnes between 2000/01 and 2019/20, (Figure 5), only 15% of this total amount was used for biofuels in 2019. About 75% of all of the world's vegetable oils are produced in developing countries, with the average price about USD 685/tonne. Although Latin America and North America produce most of the world's oilseed, the amount of vegetable oil used for biodiesel production varies, with only Argentina being a significant lipid producer and user for biodiesel production (Figure 6).

FIGURE 5. Global production of vegetable oils, 2000-2001 to 2019-2020



Source: (USDA, n.d. a).

FIGURE 6. Share of vegetable oil used for biodiesel production in different countries



Source: OECD-FAO (2020).

Used cooking oil (UCO) ranks among the most-discarded waste materials from fast food outlets, restaurants, bakeries, commercial facilities (canteens and cafeterias at office spaces, schools, universities, hospitals, etc.) and household kitchens (Pelemo, Inambao and Onuh, 2020). UCO contains high levels of free fatty acids due to chemical changes that are triggered upon frying, as well as triglycerides, and does not contain any sulphur or metallic compounds. UCO serves as a good raw material, after thorough pretreatment, for the generation of HEFA/HVO and similar fuels (even biojet fuels). UCO is used extensively for biodiesel production, but also finds use in various factories that manufacture paints, varnishes and lubricants. Pelemo, Inambao and Onuh (2020) state that 70-85% of the supply chain investment to produce such fuels is allocated to the feedstock procurement steps. Thus, by replacing expensive feedstocks with UCO, the overall production costs may be reduced and give us these fuels at a lower price than current market rates. However, it should be noted that UCO prices have been increasing as it has become a valuable commodity due to high demand. Table 2 provides estimated volumes of UCO in various regions based on multiple sources.

From Table 2 we can observe that the seven Asian countries have a potential of over 10 Mt of UCO collection. This is for two major reasons: large populations and increased oil consumption on a per-capita basis. Pavlenko and Searle (2019) found that an individual from a densely populated region of China or India has the potential to generate an average of 3-6 kg of UCO per year. It should be noted that Indonesia and Malaysia are key exporters of UCO to EU member states due to the large demand for renewable diesel production (Kharina et al., 2018).

TABLE 2. Selected UCO collection estimates based on various sources

Region	Collected UCO estimate (Mt/year)	Total potential for UCO (Mt/year)	Average collection ratio (%)	Sector	Source
Asia	2.03	10.55	19	Hotels, restaurants, caterers, household and commercial	(Cho et al., 2015; Kharina et al., 2018; Pavlenko and Kharina, 2018; Pelemo, Inambao and Onuh, 2020; Teixeira, Nogueira and Nunes, 2018; Tsai, 2019)
Oceania	0.03	0.06	50	Household and restaurants	(Bioenergy Association of New Zealand, 2015; Wang, 2013)
Middle East	0.04-0.06	0.26-0.31	15-20	Hotels, restaurants, caterers, pilgrimage centres and eateries	(Arslan and Ulusoy, 2018; Baldwin, 2017; Shahzad et al., 2017)
Africa	0.23	1.15-1.27	18-20	Hotels, restaurants, caterers, food factories and fast food centres	(Mensah and Obeng, 2013; Pelemo et al., 2020; South-South World, 2017)
South America	0.10	3.11	3	Household, restaurants and food factories	(César et al., 2017; Rincón, Cadavid and Orjuela, 2019)
North America	1.60	3.91	41	Hotels, restaurants, caterers, food factories and some household	(Chhetri, Watts and Islam, 2008; Sheinbaum-Pardo, Calderón-Irazoque and Ramírez-Suárez, 2013; Teixeira et al., 2018; Viornery-Portillo, Bravo-Díaz and Mena-Cervantes, 2020)
Europe	1.19	3.55	33	Household and commercial	(Greenea, 2017; Panadare and Rathod, 2015; Teixeira et al., 2018; Toop et al., 2014)
Subtotal	5.2 Mt/yr (or) 5.7 bn L/yr	22.7 Mt/yr (or) 25.0 bn L/yr			From data above

Notes: The following countries were considered: Asia – China, India, Indonesia, Japan, Malaysia and Republic of Korea; Oceania – Australia and New Zealand; Middle-East – Saudi Arabia, Turkey and United Arab Emirates; Africa – Egypt, Ghana and South Africa; South America – Brazil and Colombia; North America – Canada, Mexico and United States; EU27 as of 2007. As only a selection of notable countries were included in this data analysis, the figures mentioned in the table do not depict exact numbers and they increase substantially if we consider all the countries in those respective regions. See Annex A for detailed information.

In North America, Canada, Mexico and the United States collect around 1.6 Mt of UCO of which important volumes are collected in Mexico which is regarded as an important exporter to satisfy biodiesel demands in Western Africa (Viornery-Portillo et al., 2020). In the European Union, 14 member states collect UCO in large volumes, while others collect extremely low quantities (Teixeira et al., 2018). Greenea (2017) suggested that UCO collection in the Europe has still not developed to the expected levels. Notable European countries that have made an appreciable effort to collect and recycle UCO are Belgium, Germany, Italy, Netherlands, Spain and the United Kingdom of Great Britain and Northern Ireland.

UCO collections and, in turn, the potential to use UCO for various applications, vary by country as the values depend upon the eating patterns of people, collection facilities, logistical operations, storage facilities and finally, governmental legislation. Africa, the Middle East and Latin America have tremendous potential to collect and utilise more UCO than the amounts shown in the above table. For example, in Argentina and Brazil, where the combined population estimate exceeds 250 million, just 2-3% of UCO is collected.

According to the literature evaluated, around 23 Mt/yr (or 25 billion L/yr) of UCO could potentially be available (see Table 2). It should be noted that since only a selection of countries were part of this data analysis, the totals in the table do not reflect the exact numbers, which could vary significantly depending on the existence of supply chains and use of UCO for other applications.

Assuming a potential biojet fraction of 15-50% after production of HEFA from this volume, a rough estimate of 3.5-12.0 billion L/yr of biojet fuel could potentially be produced from UCO.

When the cost of a variety of FOG feedstocks is compared to the price of crude oil (Table 3) for the period 2015-2019, it is apparent that most of the feedstocks are far more costly, showing that even the price of UCO is higher than crude oil. For HEFA-derived biofuels, the feedstock cost is about 80% of the total cost of the biofuel. As well as the challenge of making a biojet fuel economically competitive with conventional jet fuel, this suggests that companies able to source cheap waste feedstocks will be at a competitive advantage.

TABLE 3. Price of vegetable oils, rendered animal fats and oils, and crude oil (USD/tonne)

Oleochemicals/lipid feedstocks (location)	2015	2016	2017	2018	2019 (Jan-Oct)
Vegetable oils					
Canola oil (Port of Vancouver)[1]	769	738	791	781	745
Soybean oil (any origin in the United States)[2]	755	814	850	789	758
Palm oil (Malaysia, CIF NW Europe)[2]	663	735	750	638	576
Rapeseed oil (Rotterdam)[2]	784	827	879	820	849
Sunflower oil (Gulf of Mexico)[2]	888	867	817	765	734
Animal fats and used cooking oil[3]					
Beef tallow, packer (Chicago)	581	638	682	556	-
Choice white grease (Missouri River)	498	537	549	463	-
Edible tallow (Chicago)	638	714	762	690	-
Edible tallow (Gulf of Mexico)	563	746	731	662	-
Lard (Chicago)	670	708	729	718	-
Poultry fat (Mid-south)	502	546	605	566	-
Yellow grease (used cooking oil) (Missouri River)	462	505	524	408	-
Crude oil – West Texas Intermediate (WTI or NYMEX)	360	320	374	477	419

Note: CIF = cost, insurance and freight.

Sources:

1 Canola Council of Canada (2019), Statistics, current canola oil, meal and seed prices, www.canolacouncil.org/markets-stats/statistics/current-canola-oil,-meal,-and-seed-prices/.

2 Indexmundi (2019), Commodity prices, www.indexmundi.com/commodities/.

3 The International Magazine of Rendering (2019), US Market Report, https://rendermagazine.com/wp-content/uploads/2019/07/Render_Apr19.pdf.

Sourcing low-carbon-intensity oleochemical feedstocks

Neste, the world's biggest renewable diesel producer, has identified 30 million tonnes of waste feedstocks worldwide that could be used to produce renewable diesel or HEFA-derived biojet (Lim, 2019).

The potential waste feedstocks that Neste has identified include (Neste, n.d. a) :

- UCO
- animal fat from the food and rendering industries
- vegetable oil processing waste and residues (e.g. palm fatty acid distillate, spent bleaching earth oil, palm effluent sludge)
- fish fat from fish processing waste
- technical corn oil (a residue from ethanol production).

Neste is also assessing other low-carbon-intensity feedstocks such as acid oil (free fatty acids), brown grease, microalgae, novel oil crops, biomass and MSW (Neste, n.d. b), with the goal of moving away from vegetable oil feedstocks by 2025. Although these potential, predominantly lipid, feedstocks should be more sustainable, their limited global availability will increase competition for their use, likely increasing their cost. The sustainability of different feedstock sources may vary substantially and must be measured through a life-cycle assessment to verify their sustainability in a specific case.

Another waste lipid feedstock is tall oil, a by-product of the pulp and paper sector, which is used by companies such as UPM for co-processing at a 30% blend with petroleum feedstocks, to produce lower-carbon-intensity fuels (UPM Biofuels, n.d.). Crude tall oil is a waste product from softwood kraft pulping and about 30-50 kg is produced for every tonne of pulp (Aryan and Kraft, 2021). Global production of crude tall oil over the past decade has been 1.5-1.8 million tonnes per year, with about 1.5 million tonnes currently used in the biochemical industry and only about 0.32 million tonnes used to make biofuels in 2018 (Aryan and Kraft, 2021).[7] In addition, crude tall oil is used for bioenergy generation.

An ongoing issue with many of these waste lipids is that some sort of pretreatment is typically required before they can be used for biofuel production (Abomohra et al., 2020). Characteristics such as their high free fatty acid content, low pH and the presence of contaminants usually implies that some sort of pretreatment will be required to limit corrosion and remove contaminants that might deactivate catalysts, for example.

The availability of lignocellulosic biomass for biojet fuel production

Biomass feedstocks including agricultural residues and woody biomass (e.g. mill or forest residues) can be used to make biojet fuel by thermochemical gasification, pyrolysis and hydrothermal liquefaction (HTL) pathways. Alternatively, biochemical approaches using sugars, alcohols (for ATJ production) or long hydrocarbons (e.g. farnesene) can be used to make biojet fuels. For example, commercial farnesene production is based on sugarcane, while isobutanol production is based on corn (Gevo, n.d. a). Although other work hopes to make biojet fuel from the lignin component of biomass, this is at a very early development stage (Murray, 2020).

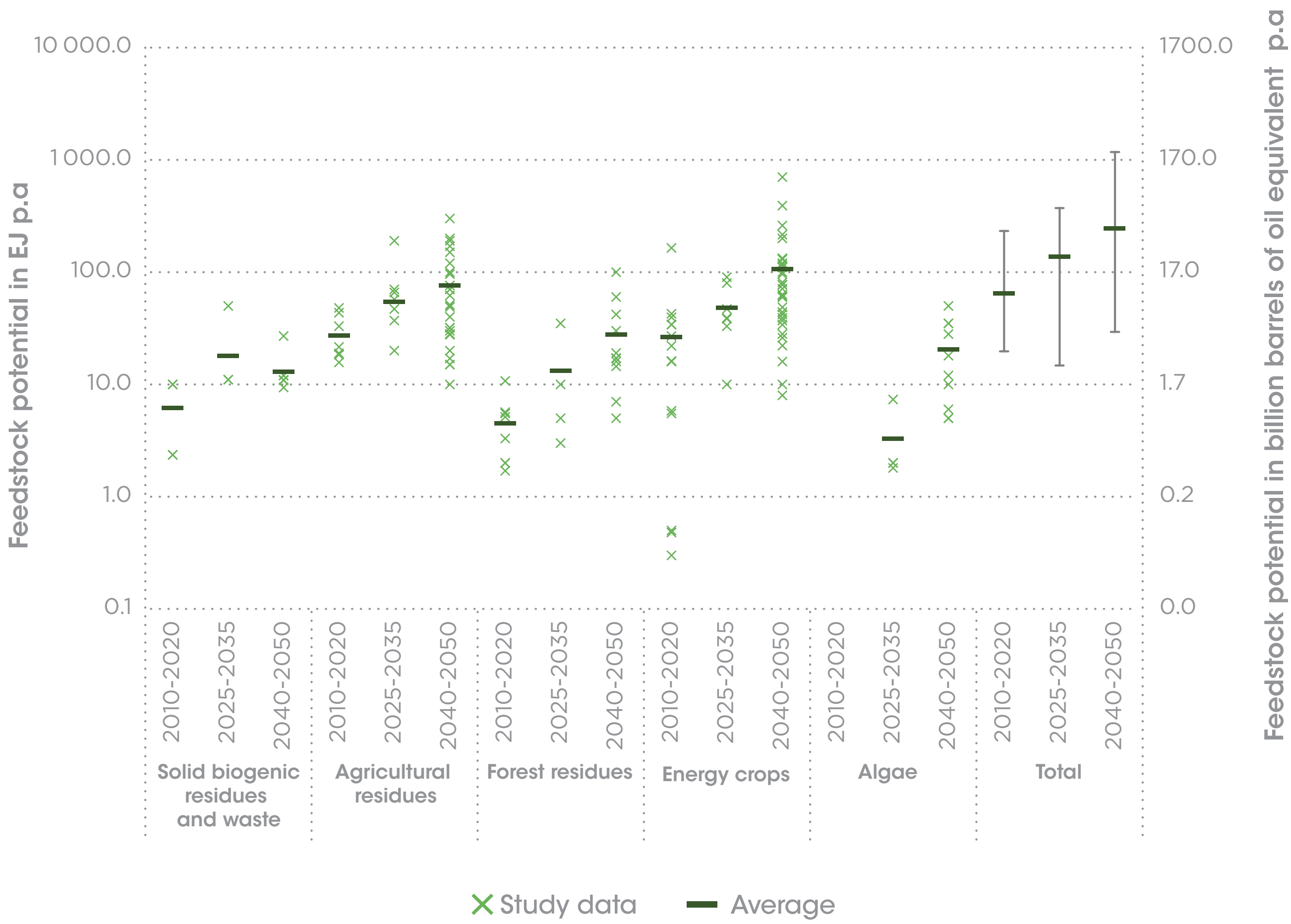
Other feedstocks that are being utilised include waste gases from steel mills, as exemplified by LanzaTech. LanzaJet will be building a demonstration plant to

7 Yield of biofuel from crude tall oil is only 50-60%.

produce 38 million litres per year of biojet fuel and renewable diesel from sustainable ethanol sources (produced from the fermentation of waste gases) with production expected to start in early 2022 (LanzaTech, 2020). This will complement the construction of an integrated biorefinery at LanzaTech's Freedom Pines site in Soperton, Georgia, using waste gases rather than biomass. The biorefinery is benefiting from a USD 14 million grant from the US Department of Energy.

Although several studies have estimated global biomass availability (Figure 7), quantifying how much of this feedstock is likely to be used to make biofuels, and more specifically biojet fuel, has yet to be attempted. Biomass is used in other applications such as the production of heat and power and biochemicals. Actual availability of biomass for biojet fuel production will therefore be influenced by competition for biomass use in other applications. Even within the biofuel pool, the likely competition between renewable diesel for road transport and biojet for aviation will have an impact. In addition, although the biomass may be available, it may prove uneconomical to harvest, or economical but not sustainable (IRENA, 2016a).

FIGURE 7. Summary of global estimates of biomass feedstock potential

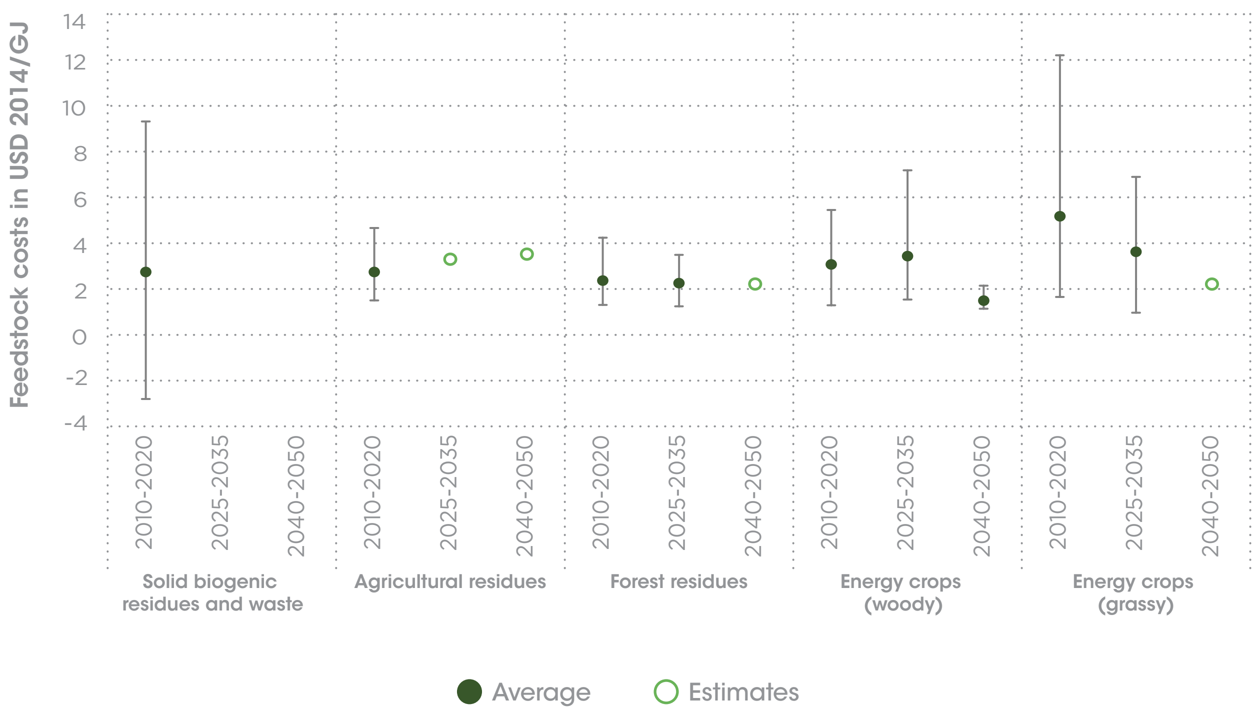


Source: IRENA (2016a).

It is widely recognised that aviation will be more difficult and costlier to decarbonise than other modes of transport, particularly as jet fuel is not a high-priced commodity. As we will discuss in more detail, unless policy drives the allocation of biomass feedstocks to biojet fuels, they are more likely to be diverted into biofuels for road transport or for bioenergy applications. Groups such as the International Council on Clean Transportation (ICCT) have estimated that competing uses will limit biomass allocation to biojet fuel production to as little as 9% of the total biomass available (Searle et al., 2019).

As summarised in Figure 8, in addition to feedstock availability, the cost estimates for different biomass feedstocks are also challenging.

FIGURE 8. Summary of global feedstock cost estimates for key biomass categories



Note: GJ = gigajoule.

Source: IRENA (2016a).

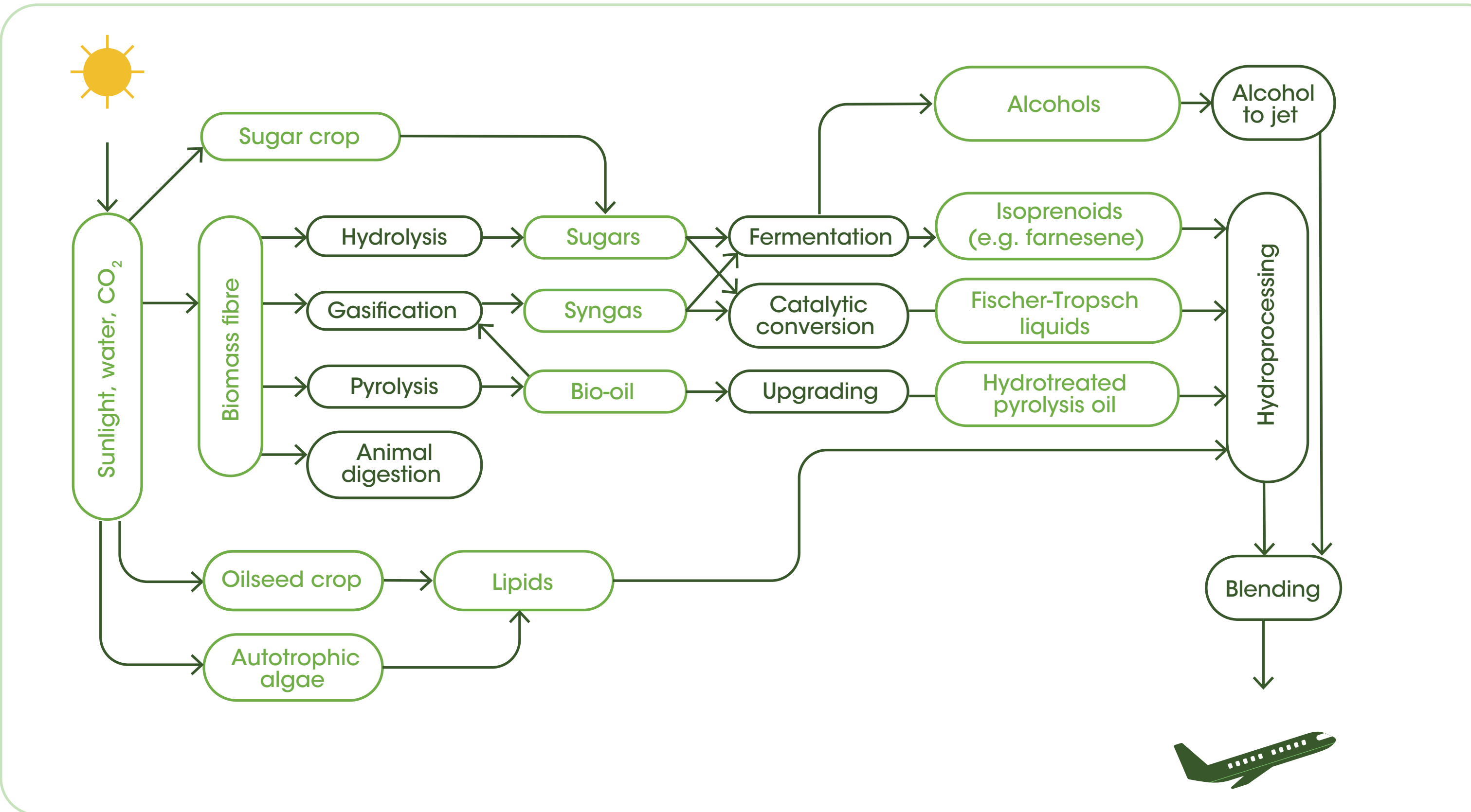
5. TECHNOLOGY PATHWAYS

FOR BIOJET FUEL PRODUCTION

As summarised in Figure 9, multiple technology pathways can be used to make biojet fuels.

Eight technology pathways are currently ASTM certified. Using any one of them provides an obvious advantage as any biojet fuel produced via these pathways will have immediate market access. Although achievement of ASTM certification typically indicates a technology readiness level (TRL) of seven, it does not in itself indicate the full commercialisation of a pathway or the availability of commercial volumes of fuel (CAAFI, 2010). If a TRL of nine is considered to be fully commercial,

FIGURE 9. Technology pathway categories for the production of biojet fuels



this means that biojet produced via the HEFA pathway is the only technology that is at this level. As described earlier, CAAFI has developed Fuel Readiness Level (FRL) and Feedstock Readiness Level (FSRL) tools to assess potential feedstock supply chains, and progression between FRL levels can take three to five years (Mawhood et al., 2016). Figure 10 provides an estimate of the commercialisation status of various technologies.

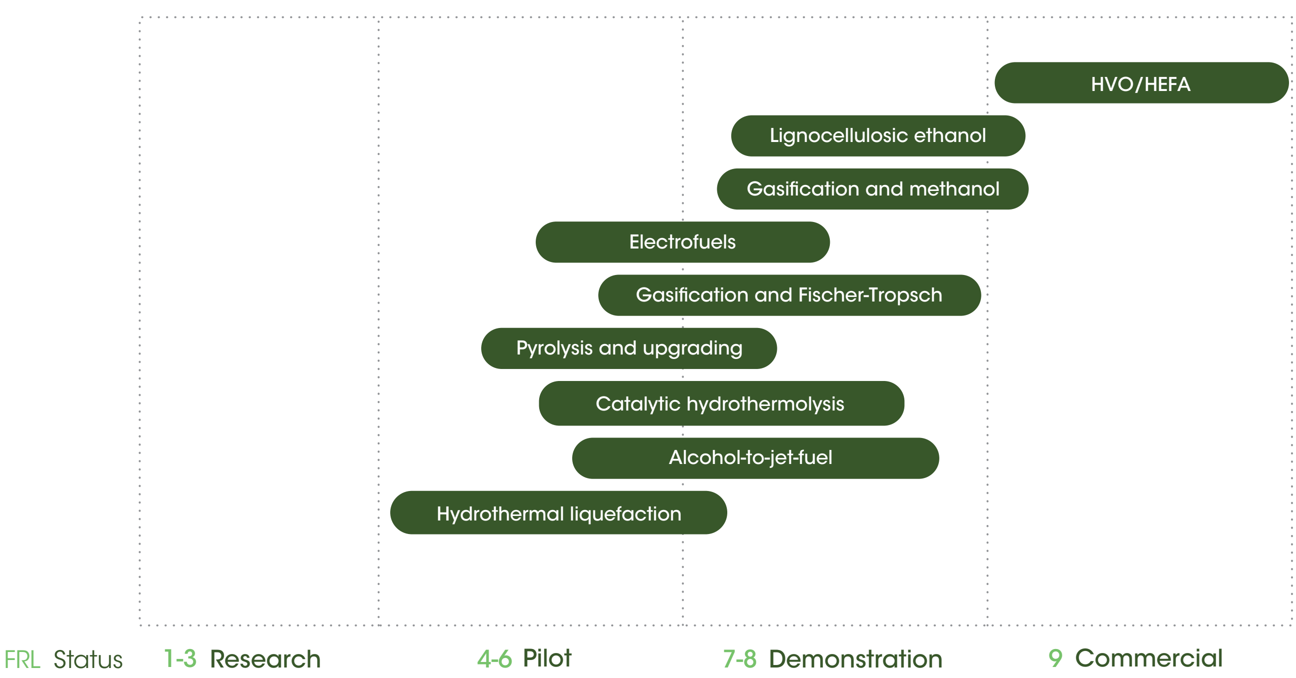
The current ASTM certification status of various biojet fuel technologies

As discussed in more detail below, the various technologies that have received ASTM certification, under ASTM D7566, first required a detailed description in an annex before they could be considered certified. Any modifications to the processes that fall outside the description must obtain a separate certification. For example, the HEFA pathway must involve hydrotreatment and if a pathway uses a different processing step, it does not fall under ASTM D7566 Annex 2. Although general minimum and maximum specifications for fuel characteristics in each pathway are described, each annex often contains further specifications unique to that pathway.

- **Annex A1:** The Fischer-Tropsch hydroprocessed synthesised paraffinic kerosene (FT-SPK) pathway was certified in 2009 for blend levels up to 50%. Feedstocks can include: renewable biomass such as agricultural and forest wastes, wood and energy crops; MSW and non-renewable feedstocks such as coal and natural gas. This is a thermochemical pathway based on gasification of feedstock prior to FT synthesis of hydrocarbons from CO and H_2.

- **Annex A2:** The synthesised paraffinic kerosene from hydroprocessed esters and fatty acids

FIGURE 10. Commercialisation status of various biofuel pathways based on fuel readiness level



(HEFA-SPK) pathway was certified in 2011 for blend levels up to 50%. Feedstocks include plant oils and animal FOGs. It should be noted that only hydrotreatment processing is included under this annex. Therefore, processes using other methods are currently not included, even where FOGs are used as feedstock.

- **Annex A3:** The synthesised iso-paraffins from hydroprocessed fermented sugars (SIP-SPK) pathway was certified in 2014 at blend levels up to 10%. Feedstocks include sugars from any source. This biochemical pathway uses modified yeasts to ferment sugars into C15 hydrocarbon molecules, farnesene, which has to be further hydrotreated to produce farnesane.

- **Annex A4:** The synthesised paraffinic kerosene with aromatics (SPK/A) pathway involves alkylation of light aromatics from coal feedstock, although it automatically applies to biomass-based feedstocks. The pathway was certified in 2015 for blend levels up to 50%. The potential feedstocks are the same as described in Annex A1. This is a thermochemical process based on gasification and FT synthesis with the addition of alkylation of light aromatics (primarily benzene) to create a hydrocarbon blend that includes aromatic compounds. This is the only approved process that includes aromatics in the biocomponent, unlike the other processes where only paraffinic hydrocarbons are produced.

- **Annex A5:** The alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK) pathway was certified in 2016 (using an isobutanol intermediate) and 2018 (using an ethanol intermediate) for blend levels up to 50%. Feedstocks can include sugars from starches, e.g. corn, sugarcane or sugar beet, or from cellulosic biomass. The pathway using an ethanol intermediate was based on the LanzaTech process, which involves the fermentation of CO_2 off-gases to ethanol. The production of the alcohol intermediate, using a biochemical fermentation process, is followed by the production of hydrocarbons, using dehydration, oligomerisation and hydrogenation to yield hydrocarbons.

- **Annex A6:** The catalytic hydrothermolysis jet (CHJ-SPK) pathway received certification in February 2020. It is based on fatty acid esters and free fatty acids as a feedstock and a hydrothermal liquefaction technology. The blending of up to 50% is permitted. The product contains paraffins, isoparaffins, cycloparaffins and aromatic compounds over the jet and diesel boiling point range and fractionation is required to produce jet and diesel.

- **Annex A7:** The synthesised paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids (HC-HEFA-SPK) pathway received certification in May 2020. The current approved source of the bio-derived lipids is from *Botryococcus braunii,* a microalgal species, and up to 10% blends with conventional petroleum jet fuel are permitted. This was the first biojet certified through the express process.

- **Co-processing:** The co-processing of lipids within existing petroleum refineries was granted certification in April 2018 under 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 FT liquids at 5% blends in existing refineries was approved in 2020.

Other technologies are in the certification pipeline, but the process is often time-consuming and rigorous to ensure equivalent performance and safety. As the process has also proven to be expensive, recent improvements hope to address these shortcomings by the use of an express process and centralised, one-stop-shop testing and analysis.

Strengths and challenges of the various technology routes used to make biojet fuels

HEFA/HVO

HEFA or HVO are produced via the hydroprocessing of lipids/oleochemicals. The technology is fully commercial and relatively straightforward when compared to other technologies, as well as scalable (large facilities are possible, more than 1 billion litres per year). The HEFA pathway to biofuels results in the production of about a 15-20% biojet fraction, with the remaining 80% predominantly in the form of renewable diesel.[8] As biojet production in most facilities typically requires additional processing steps (e.g. hydrocracking and isomerisation), the majority of the liquid fraction is sold as renewable diesel. This is partly due to favourable policies in jurisdictions such as California incentivising the production of renewable diesel and partly due to the additional cost of the infrastructure required to make the biojet fraction. Currently, World Energy and Neste produce biojet as part of their product portfolios. As noted earlier, Neste is currently expanding the infrastructure needed to increase their production of biojet.

The two main challenges with the HEFA route to biojet fuels are the high cost of the oleochemical feedstock and potential sustainability concerns when using crop-based vegetable oils. This has resulted in the increased sourcing and use of FOGs, which has precipitated a corresponding increase in the price of waste lipids. As a result, international competition for oleochemical feedstocks is increasing as several biofuels, including biodiesel, renewable diesel and biojet fuels can all be made from lipids. Repurposed refineries, such as World Energy and the recently announced Phillips 66 refinery,[9] as well as those refineries adopting a co-processing strategy, will all be competing for the same oleochemical/lipid feedstocks. Although this route will continue to be the predominant technology used to make biojet fuel, the potential global scale of "conventional biojet fuel" production will be influenced by feedstock availability, cost and overall sustainability, rather than specific technical challenges per se.

Thermochemical technologies for biomass-to-biojet

In contrast, the major challenges for thermochemical routes to biojet are less about feedstock and more about technology risks/maturity and conversion process efficiency. Thermochemical routes of biomass-to-biojet involve the co-production of the three main products of bio-oil, synthesis gas and char, with the two main thermochemical routes to drop-in biofuels being gasification and pyrolysis/HTL. Gasification combined with FT synthesis can produce biojet fuel and, as mentioned earlier, this pathway is ASTM certified. The pyrolysis route to biojet has also been termed hydrotreated depolymerised cellulosic jet (HDCJ).

A number of commercial facilities based on gasification-FT are planned and under construction, and this pathway is discussed in more detail below.

GASIFICATION

Gasification typically involves heating biomass particles at high temperatures to produce synthesis gas (syngas, comprised mostly of H_2 and CO), with the syngas subsequently upgraded (catalytically condensed) to

8 When additional processing is carried out to maximise the jet fraction, up to 50% can be achieved.

9 https://biofuels-news.com/news/phillips-66-plans-worlds-largest-renewable-fuels-plant/ (accessed 10 December 2020).

liquids/fuel via the FT process. The process produces a mixture of hydrocarbon molecules from which fuels, including diesel, jet, gasoline and other chemicals can be extracted. The FT process is also used in the world's largest natural gas-to-liquids facility (Shell's Pearl GtL facility in Qatar, completed in 2011), which produces 140 000 barrels of fuel per day (~22 million litres per day).

Although biojet could potentially be produced using biomass or bio-oil as the feedstock, due to various challenges biojet fuel commercialisation based on biomass has been very slow. For example, gasification of biomass typically results in considerable tar formation that needs to be cleaned up, while the high oxygen content of biomass affects the composition of the syngas (ratio of H_2 to CO). As a result, biomass-derived syngas is less energy-dense than natural gas, plus it also contains a level of impurities. Typically, biomass- and MSW-derived syngas needs to be enriched with hydrogen and cleaned of the impurities such as tars, nitrogen and other heteroatoms that can deactivate the synthesis catalysts (Karatzos et al., 2014; Rhyner, 2016).

It should also be noted that gasification technologies typically involve high capital costs to both gasify the biomass and convert the resulting syngas to FT liquids (Swanson et al., 2010). The capital costs for construction of the Fulcrum Bioenergy and Red Rock Biofuels facilities are estimated at USD 4 560-5 560 per kilowatt (kW) (USD 200-355 million) (IRENA and The Methanol Institute, 2021). It is also worth noting that, as biomass is a less energy-dense feedstock, logistical challenges can be anticipated, while typical FT technologies result in only about 40% of the final product being jet fuel and middle distillates (Pavlenko et al., 2019).

The Fulcrum Bioenergy and Red Rock Biofuels facilities are currently under construction and will be commercial biomass gasification to drop-in biofuel producers. Fulcrum hopes to keep costs down by using MSW as the feedstock, while Red Rock plans to use woody biomass. These pioneer plants should provide invaluable insights and pave the way for more extensive commercialisation based on lessons learnt. It has been suggested that the gasification-FT route has considerable scope for cost reductions as the technology matures.

PYROLYSIS/HTL

Although companies such as Ensyn in Canada have been producing fast pyrolysis bio-oils for many years, these "biocrudes" have mainly been used in niche applications, such as food flavouring (barbeque flavour), while energy applications have been restricted to heavy fuel oil used in stationary heating and power generating facilities (IRENA, 2017). While Ensyn[10] has obtained regulatory approval for its drop-in fuels, RFDiesel and RFGasoline, based on co-processing in oil refineries, to date it has produced no jet fuel.

Biojet fuel produced via the pyrolysis route is still in development as the biocrudes contain up to 40% oxygen (similar to the biomass itself), resulting in the need for extensive upgrading to produce liquid hydrocarbon fuels, including the biojet fraction. As upgrading is typically achieved via hydroprocessing, the need for additional sources of hydrogen is likely to result in additional equipment and production costs (Jones et al., 2013), while the acidity and other pyrolysis oils' characteristics will also affect the cost and stability of the catalysts.

A pyrolysis approach for biocrude production and upgrading to biojet has the advantage that it can also make use of existing oil refinery infrastructure through

10 www.ensyn.com/2015/08/26/ensyn-receives-key-regulatory-approval-for-its-renewable-diesel/.

a co-processing strategy, which will reduce the capital and operating costs of making biojet. Several technical challenges to co-processing biocrudes still exist, such as the point of biocrude insertion, the extent of upgrading required prior to insertion, and the different catalysts needed to upgrade biocrudes. However, co-processing of pyrolysis biocrudes in existing petroleum refineries could be a key strategy for producing lower-carbon-intensive jet fuels (Van Dyk et al., 2019a).

It has been shown that processes such as HTL can produce a biocrude/bio-oil intermediate with a significantly lower oxygen content, which would be easier to upgrade to biojet fuels. Although some studies have indicated that this could potentially lower the cost of biojet fuels (de Jong, Antonissen et al., 2017), challenges such as the high pressures used in the HTL process are likely to prove problematic at scale.

Alcohol-to-jet

The alcohol-to-jet (ATJ) fuel process has been demonstrated with two alcohol intermediates, isobutanol and ethanol, receiving ASTM certification for use in 50% blends with conventional jet fuel. Theoretical jet yields of up to 70% are possible, with gasoline being the other product. Although this yield is considerably higher than that achievable via the HEFA or thermochemical pathways, an ongoing challenge is the value of the alcohol intermediate. For example, isobutanol has a higher market value as a chemical than as a potential biojet fuel feedstock. Ethanol has a similar challenge, being used extensively in road transport. The overall sustainability of feedstock will also need to be considered as it will affect the carbon intensity of the final biojet fuel. Although corn-based feedstocks can result in low-carbon-intensive fuels, lignocellulosic biomass-based feedstocks are anticipated to provide much greater emission reductions (ICAO, 2019d).

Ethanol-to-jet fuels based on "waste" gases (LanzaJet/LanzaTech)

The LanzaTech technology pathway is based on the microbial fermentation of off-gases from steel mills to produce ethanol and other products (LanzaTech, n.d.). In 2020, LanzaTech launched the company LanzaJet, which will solely focus on making biojet fuels via this pathway. LanzaJet has several investors, including Canadian energy company Suncor Energy Inc., Japanese trading and investment company Mitsui & Co., Ltd and Shell (LanzaJet, n.d.). The consortium hopes to build a demonstration plant that will produce 38 million litres per year of sustainable aviation fuel and renewable diesel using sustainable ethanol sources, with production expected to start in early 2022. The participation of All Nippon Airways and British Airways has also been reported. LanzaTech obtained a USD 14 million grant from the US Department of Energy, which is being used to construct an integrated biorefinery at LanzaTech's Freedom Pines site in Soperton, Georgia.

Electrofuels (power-to-liquids)

Electrofuels, also known as power-to-liquids (PtL), are drop-in fuels that, in theory, can provide very low-carbon-intensity transport fuels. The key process step is the utilisation of renewable energy sources (wind, hydro, solar) to electrolyse water and produce hydrogen. When the "green" hydrogen is combined with "green" or waste carbon sources, CO or CO_2, via processes such as FT synthesis, hydrocarbon fuels can be produced, including a jet fraction. The CO/CO_2 can also be obtained via direct air capture. Companies such as Sunfire GmbH are commercialising this technology[11] and form part of the Norsk e-fuel consortium.

11 www.sunfire.de/en/home.

Although this technology has considerable potential to reduce emissions, the availability of excess renewable electricity is a critical component. The estimated cost of electrofuels relative to other technologies is challenging, as can be seen in Table 4, which compares minimum fuel selling prices (MFSPs) for different pathways. Groups such as the ICCT suggest that electrofuels can only be produced economically when significant policy incentives are in place to price carbon. It has also been emphasised that electrofuels can only deliver climate benefits if strict sustainability standards are ensured (Transport & Environment, 2017). The cost of electrofuels may vary depending on the sources of carbon and hydrogen. While cost improvements are expected over time, competitiveness with other biojet fuels is likely to remain challenging for the near future. Electrofuels can potentially provide very significant emission reductions, even negative emissions where produced from CO_2 from direct air capture and bioenergy with carbon capture and storage.

"Other" routes to biojet fuels

While there are several companies pursuing variations of these technologies, many of the technologies are still at the research stage and likely many years away from commercialisation, for example lignin-to-drop-in biofuels (Cao et al., 2018). The common challenge with any of the bio-based feedstocks is the need for cost-effective removal of the oxygen from the feedstock to make a hydrocarbon. This is the reason why feedstocks such as lipids and lignin are preferred to sugars and alcohols. As described below, if we can make use of current facilities to both deoxygenate and upgrade bio-feedstocks while decarbonising fossil fuels at the same time, this might be a preferred way to increase the production of biojet fuels or at least partially decarbonise jet fuels.

Co-processing of bio-based intermediates in existing refinery infrastructure

During the production of drop-in biofuels, including biojet, many of the processes used to upgrade the fuels are almost identical to those used in conventional oil refineries. Infrastructure such as catalytic cracking, hydrocracking and hydrotreatment has high capital cost and operates at a scale that is difficult to reproduce in a biorefinery (Van Dyk et al., 2019b). In addition, upgrading requires hydrogen, most frequently produced through a large-scale steam reformer located at the petroleum refinery. Thus, potential biojet fuel-focused biorefineries could reduce costs through integration with petroleum refineries in a number of ways. These could include co-processing by insertion of bio-based liquid intermediates into an existing refinery. The main liquid intermediates considered for insertion into a refinery are lipids, bio-oils/biocrudes and FT liquids.

Co-processing of 5% lipids is an ASTM-certified process and is already carried out commercially at refineries such as BP's Cherry Point in Washington State (BP, n.d.) and the Parkland Refinery in Burnaby, British Columbia. Co-processing of tall oil fatty acids has been carried out successfully for some time at 30% blends by companies such as Preem in Sweden (Egeberg, Michaelsen and Skyum, 2010). Co-processing of thermochemical liquid intermediates such as pyrolysis or HTL biocrudes is undergoing trials and is currently the focus of substantial research. However, only limited biocrude volumes are currently available, plus biocrudes are also significantly more complex than lipids, resulting in considerable upgrading challenges. However, as biocrudes are mainly produced from biomass, which should be cheaper and available in greater quantities than lipids, it has been suggested that biocrude-based technologies will be better able to supply the significant volumes of lower-carbon-intensive jet fuels that will be needed in the future.

Although co-processing can be carried out in the fluid catalytic cracker and the hydrotreater/hydrocracker, it is most likely that biojet fuels will be produced by co-processing in the hydrotreater/hydrocracker (Van Dyk et al., 2019b), as the fluid catalytic cracker is mainly used to produce gasoline. To date few technical challenges have been encountered when using a 5% co-processing blend (Van Dyk et al., 2019b).

By co-processing lipids or biocrudes at existing refineries, companies can produce lower-carbon-intensity fuels, substantially increasing the volumes of fuel available at a much lower capital cost compared to freestanding biorefineries. Policies such as California and British Columbia's LCFS can motivate refineries to use a co-processing strategy as one way of meeting their carbon reduction targets. Detailed costs analyses are not available to determine the comparative advantage of co-processing versus freestanding production. Biojet production through co-processing is limited to a 5% insertion rate at the refinery (based on ASTM certification).

6. THE ICAO CORSIA

ICAO members have agreed that global market-based measures will be one of the strategies used to address the environmental impact of the aviation sector. The ICAO CORSIA is designed to work in conjunction with efficiency improvements, innovative technologies and biojet fuels to achieve the indicated carbon reduction targets. However, to achieve carbon-neutral growth, offsets will be used by the airlines as an interim measure by financing emission reductions in other sectors.

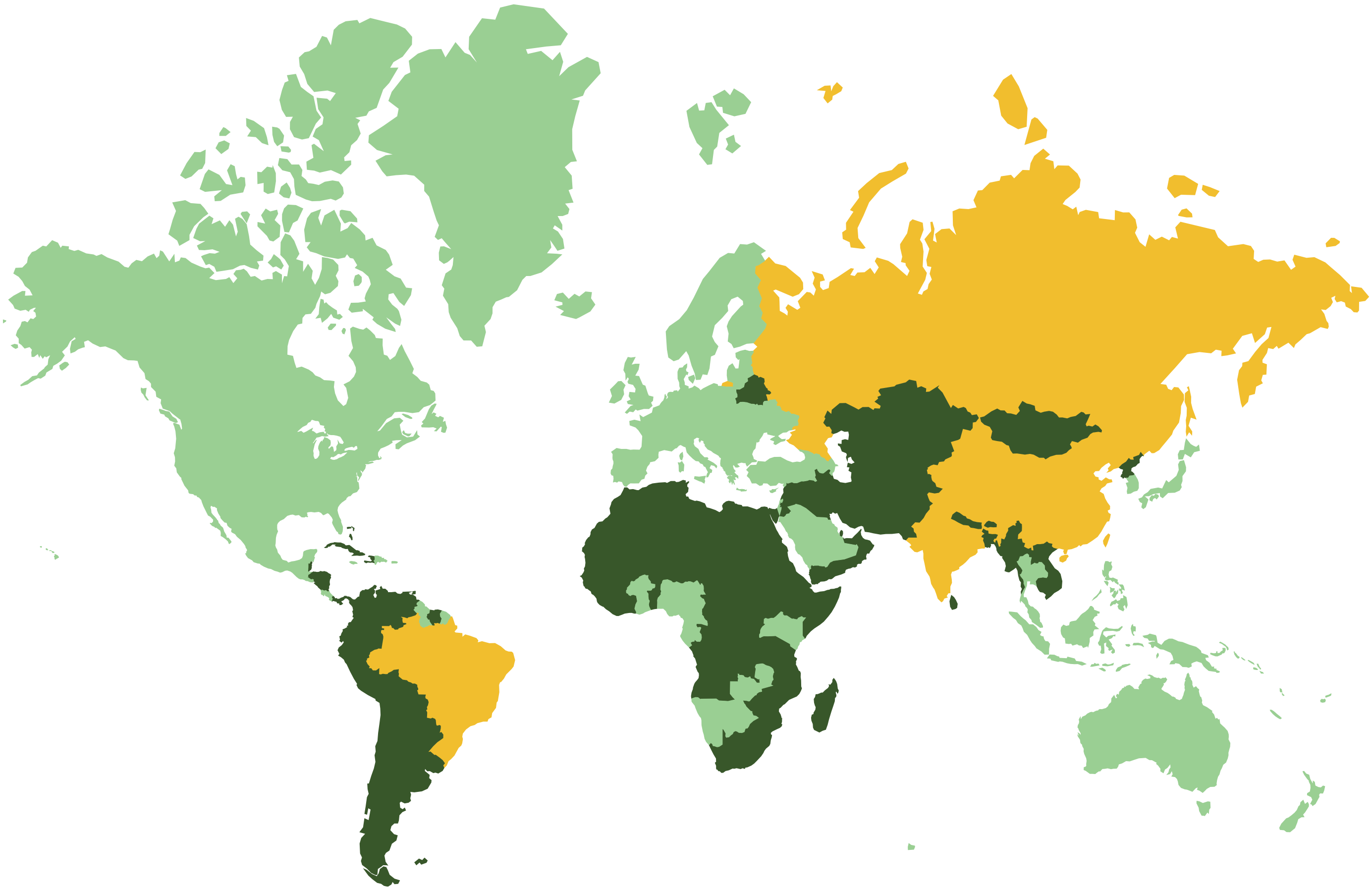
Until the COVID pandemic, the airline sector's baseline emissions were due to be defined as an average of the 2019 and 2020 international flight emissions, with the offset requirements calculated against this baseline to ensure carbon-neutral growth. However, as a result of the pandemic, only the 2019 emissions will be used as the baseline.

Although the initial pilot phase of CORSIA will take place from 2021 to 2023, followed by a voluntary phase during 2024-2026, after this time the CORSIA-derived targets will be mandatory for all members unless they have obtained an exemption. Exceptions will include flights to and from least-developed countries, small island developing states, landlocked developing countries and states/countries that represent less than 0.5% of international revenue tonne kilometres. However, some exempt states may still volunteer to participate. The countries/regions that will participate or who are exempt from the various phases are summarised in Figure 11.

As of July 2020, 88 states had volunteered to participate in CORSIA, and while emissions from all international flights have to be reported to ICAO, offsets will only be required for emissions of those flights between volunteering countries (Aviation Benefits Beyond Borders, 2020).

The monitoring and reporting regulations and calculation of offset obligations have been summarised previously and can be accessed in recent IATA and ICAO publications (IATA, 2019a; ICAO, 2019c).

FIGURE 11. Map illustrating participation of states in CORSIA



Source: DW (2020); IATA (2018).

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any official endorsement or acceptance by IRENA.

CORSIA's potential impact on biojet fuels

As described earlier, the purchase of CORSIA-endorsed offsets/emission reductions is likely to occur via projects or programmes outside the aviation sector. Airlines can also meet offset obligations by using "CORSIA eligible fuel(s)", which are, as described earlier, defined as a "CORSIA sustainable aviation fuel" or a "CORSIA lower carbon aviation fuel" (ICAO, 2019c). A CORSIA sustainable aviation fuel is further defined as a "renewable or waste-derived aviation fuel that meets the CORSIA sustainability criteria" as determined by ICAO (ICAO, 2019c). It should be noted that, ideally, CORSIA would motivate airlines to use biojet fuels to meet their emission reductions rather than purchasing offsets. However, some groups have suggested that the overall CORSIA approach will result in minimal impact on real in-sector emissions as it will be cheaper to purchase offsets than purchase biojet fuels (Pavlenko, 2018; Searle et al., 2019).

Thus, it is probable that the price of offsets will influence CORSIA's ability to promote biojet fuel development, particularly if an airline is able to purchase offsets at a lower price than what they would pay for biojet fuel to achieve similar emission reductions. Based on an offset price of USD 23 per tonne of CO_2, a biojet fuel would be a more attractive, economical option if the price of the biojet fuel were only USD 0.037 per litre more expensive than conventional jet fuel (Hitchcock, 2019).[12]

An ongoing challenge is that the price of carbon offsets is affected by market dynamics, with the average price of offsets about USD 3.00/tonne of carbon dioxide equivalent (CO_2-eq) in 2019 (Carbonmarketwatch, 2020). It is also apparent that both the nature of the project and the standard of environmental integrity will play a role in pricing. CORSIA has already approved six offset programmes while placing limits on the "age" of offsets (only projects started after 1 Jan 2016 are accepted) and the type of project (Carbonmarketwatch, 2020; ICAO, 2020a). However, several groups have indicated that these definitions are not restrictive enough and that "junk" offsets might be purchased without providing significant environmental benefits (Carbonmarketwatch, 2020). To address these concerns, the eligibility of the various offset programmes and the types of project that might be approved will be reviewed by CORSIA before the end of the pilot phase in 2022 (ICAO, n.d.).

Although it has been speculated that the limited supply of offsets could increase their cost, other studies have indicated that sufficient offsets should be available to allow customers to meet their CORSIA obligations (Cames et al., 2015; Ecosystem Marketplace, 2020). For example, during the pilot phase, demand for offsets is estimated to be 44-158 million credits, while the potential supply (based on ICAO restrictions that exclude millions of low-quality offsets) should be 180-570 million credits. However, demand estimates were made prior to COVID-19, which is likely to have a significant impact on airline offset obligations during the initial phase (Carbonmarketwatch, 2020).

12 One tonne of jet fuel produces 3.16 tonnes of CO_2 upon combustion. Hitchcock's calculations are based on US tons. The price of conventional jet fuel has fluctuated significantly during the COVID pandemic. The price of HEFA biojet in September 2020 was USD 2 124 per tonne, six times more than the price of conventional jet fuel at that time (Argusmedia, 2020).

7. ACHIEVING COST-COMPETITIVENESS
WITH CONVENTIONAL JET FUEL

Biojet fuel is significantly more expensive than conventional jet fuel and is likely to remain so for some time to come. Estimates of the price difference vary from 2-7 times (IATA, 2015a) to 3-4 times higher (Hollinger, 2020). Although airlines and airports have signed several offtake agreements, the price of the biojet fuel in these contracts is not publicly disclosed. Thus, it has proven difficult to project accurate prices for biofuels, with most cost estimates derived from sources such as reports, online media, presentations and academic papers (Bann et al., 2017; IATA, 2015a, 2015b; de Jong et al., 2015; de Jong, Hoefnagels, et al., 2017; Pavlenko et al., 2019; Staples et al., 2014; Yao et al., 2017; Zhao, Yao and Tyner, 2016).

As already noted several times, the HEFA-based production of biojet fuels is the only fully commercial technology for which fairly reliable and accurate information is available. Many of the techno-economic analyses of other "advanced" biojet fuel technologies have been based on modelling and assumptions. For example, these studies often assume "nth plant" costs and operation, even though "pioneering" commercial facilities are often as much as 50% more expensive (de Jong et al., 2015). Table 4 presents a summary of projected MFSPs[13] based on techno-economic analyses carried out in multiple studies. Significant variation is observed according to technology, feedstock and other factors.

13 MFSP is based on achieving a net present value (NPV) of zero.

TABLE 4. Summary of minimum fuel selling prices (MFSP)s of biojet fuel for different technology pathways as calculated by different authors based on techno-economic assessments

Technology	Feedstock type	MFSP in units used in reference	MFSP in USD/tonne	Source
HEFA/HVO	UCO	EUR 30.8/GJ	1 593	(de Jong et al., 2015)
	Yellow grease	USD 0.66-1.24/L	825-1 550	(Bann et al., 2017)
	Tallow	USD 0.79-1.42/L	988-1 775	(Bann et al., 2017)
	Soybean oil	USD 0.87-1.60/L	1 086-2 000	(Bann et al., 2017)
	Jatropha oil	EUR 2 000/tonne	2 360	(Neuling and Kaltschmitt, 2018)
	Palm oil	EUR 890/tonne	1 050	(Neuling and Kaltschmitt, 2018)
	Vegetable oil	USD 2.22/kg	2 220	(Diederichs et al., 2016)
	UCO	EUR 51-91/MWh	721-1 089	(Brown et al., 2020)
Gasification/FT	Forest residues/wheat straw	EUR 41.1-60.5/GJ	2 124-3 127	(de Jong et al., 2015)
	Biomass	EUR 75-144/MWh	898-1 724	(Brown et al., 2020)
	All wastes	EUR 53-104/MWh	635-1 245	(Brown et al., 2020)
	MSW	USD 0.95-1.39/L	1 188-1 738	(Bann et al., 2017)
	Lignocellulose	USD 2.44/kg	2 440	(Diederichs et al., 2016)
Pyrolysis, bio-oil and upgrading	Forest residues/wheat straw	EUR 29.68-42.24/GJ	1 534-2 183	(de Jong et al., 2015)
	Forest residues/wheat straw (bio-oil co-processing)	EUR 79-139/MWh	946-1 664	(Brown et al., 2020)
	Forest residues/wheatstraw (bio-oil stand-alone)	EUR 82-127/MWh	982-1 520	(Brown et al., 2020)
	Forest residues/wheatstraw (FP bio-oil)	USD 3.39/gallon	1 120	(Jones et al. 2013)
	Woody biomass (FPH)	USD 1.02–2.10/L	1 275-2 625	(Bann et al., 2017)

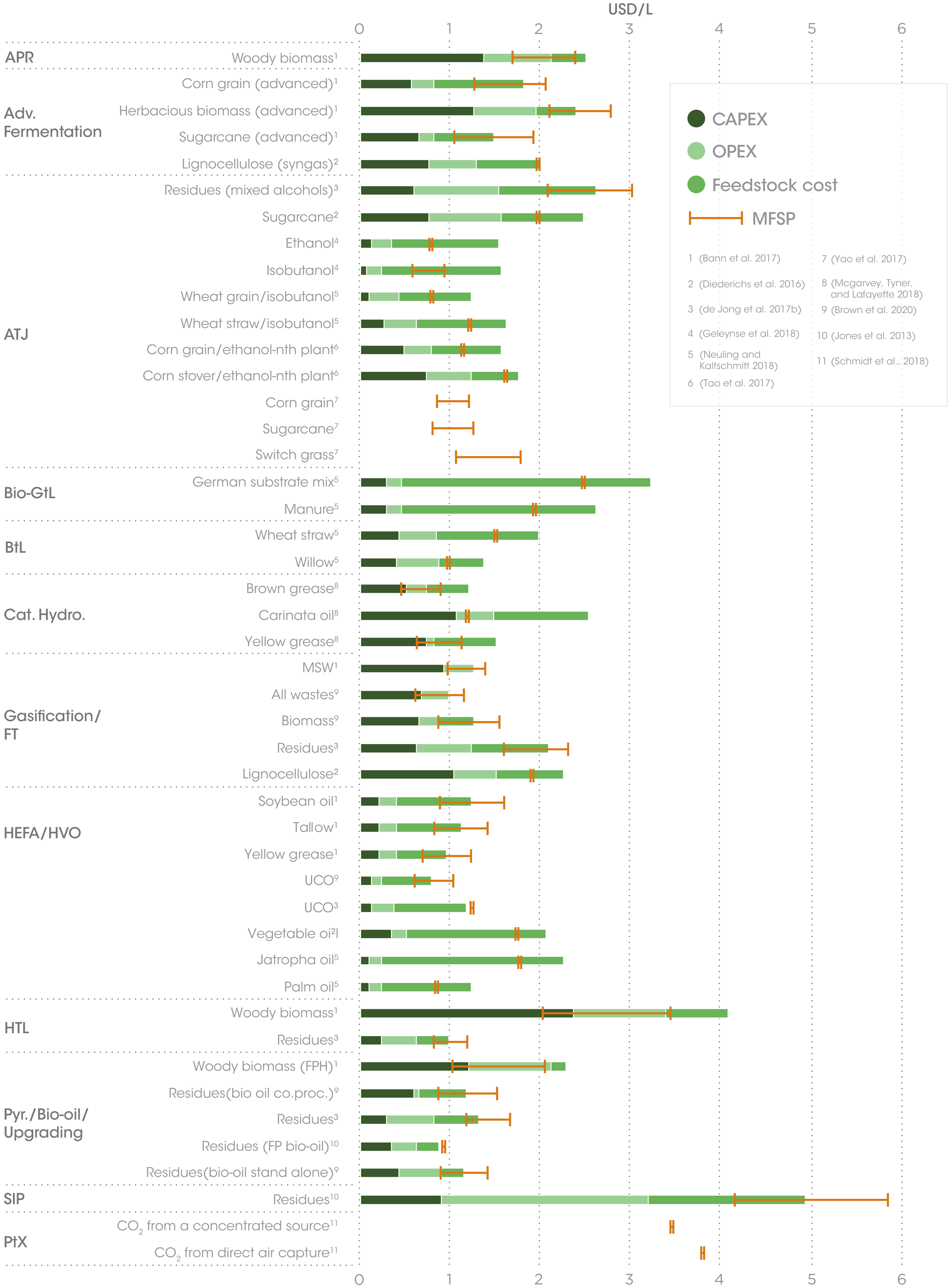
ATJ	Forest residues (mixed alcohols)	EUR 54.80-79.91/GJ	2 832-4 130	(de Jong et al., 2015)
	Ethanol	USD 2.84/gallon	938	(Geleynse et al. 2018)
	Isobutanol	USD 2.23-3.37/gallon	736-1 113	(Geleynse et al. 2018)
	Wheat straw/isobutanol	EUR 1 325/tonne	1 564	(Neuling and Kaltschmitt, 2018)
	Wheat grain/isobutanol	EUR 827/tonne	976	(Neuling and Kaltschmitt 2018)
	Corn grain/ethanol-nth plant	USD 4.20/gallon	1 387	(Tao et al. 2017)
	Corn stover/ethanol-nth plant	USD 5.37/gallon	1 773	(Tao et al. 2017)
	Sugarcane	USD 0.96/L	1 200	(Yao et al. 2017)
	Corn grain	USD 1.01/L	1 263	(Yao et al. 2017)
	Switch grass	USD 1.38/L	1 725	(Yao et al. 2017)
	sugarcane fermentation	USD 2.54/kg	2 540	(Diederichs et al. 2016)
Advanced Fermentation	Sugarcane (advanced)	USD 1.10–1.96/L	1 375-2 450	(Bann et al., 2017)
	Corn grain (advanced)	USD 1.30–2.10/L	1 625-2 673	(Bann et al., 2017)
	Herbaceous biomass (advanced)	USD 2.16–2.92/L	2 700-3 650	(Bann et al., 2017)
	Lignocellulose (syngas)	USD 3.43/kg	3 430	(Diederichs et al. 2016)
Catalytic hydrothermolysis	Brown grease	USD 2.51/gallon	829	(Mcgarvey, Tyner, and Lafayette 2018)
	Yellow grease	USD 3.52/gallon	1 162	(Mcgarvey, Tyner, and Lafayette 2018)
	Carinata oil	USD 5.35/gallon	1 767	(Mcgarvey, Tyner, and Lafayette 2018)

Biogas to liquids (Bio-GtL)	German substrate mix	EUR 2 854/tonne	3 368	(Neuling and Kaltschmitt, 2018)
	Manure	EUR 2 178/tonne	2 570	(Neuling and Kaltschmitt, 2018)
	Wheat straw	EUR 1 680/tonne	1 982	(Neuling and Kaltschmitt, 2018)
	Willow	EUR 1 054/tonne	1 244	(Neuling and Kaltschmitt, 2018)
Hydrothermal Liquefaction (HTL)	Forest residues/wheat straw	EUR 20.55-29.68/GJ	1 062-1 530	(de Jong et al., 2015)
	Woody biomass	USD 2.09–USD 3.58/L	2 613-4 475	(Bann et al., 2017)
SIP	Forest residues/wheat straw	EUR 109.59-146.12/GJ	5 664-7 552	(de Jong et al., 2015)
Aqueous phase reforming (APR)	Woody biomass	USD 1.73–2.48/L	2 163-3 100	(Bann et al., 2017)
PtX and FT	CO_2 from direct air capture	EUR 4 215/tonne	4 974	(Schmidt et al., 2018)
	CO_2 from a concentrated source	EUR 3 245/tonne	3 829	(Schmidt et al., 2018)

* The study by Brown et al. (2020) was based on advanced biofuels cost estimates and is not specifically focused on jet fuel, unlike the other studies.

Notes: FPH = fast pyrolysis and hydroprocessing; PtX = Power-to-X; SIP = synthesised iso-paraffins. Exchange rate used for conversions EUR 1 = USD 1.18. Density of jet fuel = 0.8 kg/L. Calorific value of jet fuel = 43.8 MJ/kg (or) 43.8 GJ/tonne. Conventional jet fuel price as on 13 November 2020 = USD 0.264/litre = USD 361/Mt (www.iata.org/en/publications/economics/fuel-monitor). This price was 41.5% lower than in November 2019.

FIGURE 12. Breakdown of biojet cost from various references to illustrate CAPEX, OPEX and feedstock cost



Notes: Adv. = advanced; APR = aqueous phase reforming; BtL = biomass to liquids; Cat. Hydro. = Catalytic hydrothermolysis; FPH = fast pyrolysis and hydroprocessing; GtL = gas-to-liquids; Pyr. = pyrolysis; Breakdown of cost elements was calculated based on the corresponding studies and the numbers could be different from the original study.

Figure 12 shows the estimated MFSPs for different biojet technologies according to a number of publications and the production costs, broken down by capital expenditure (CAPEX), operating expenditure (OPEX) and feedstock cost (see Annex B). MFSP represents the break-even price at which fuel products have to be sold to attain a zero NPV. It may include additional costs or benefits compared to the production cost, such as tax credits, additional infrastructure cost, environmental benefits and by-product revenue.

HEFA is currently the most commercialised technology option, with low CAPEX and OPEX, but with high feedstock cost (Figure 12). Feedstock costs vary depending on the source, and waste-based feedstock such as UCO or tallow can lead to a significant reduction in the overall fuel production costs. HEFA is expected to play a pivotal role as a primary, short-term accelerator for biojet, but availability of sustainable oil-based raw material will become limiting. These feedstocks are already used extensively for biofuels in the road transport sector and biojet is likely to be in competition with renewable diesel for them.

Figure 12 also demonstrates that gasification/FT has relatively higher CAPEX and OPEX than HEFA/HVO. Higher capital investment is mainly due to the installation of boilers, treatment of high levels of contaminants present in the feedstock, gas-cleaning devices, ash disposal systems and storage facilities for syngas. With sufficient improvements in process design and operational conditions, reduced plant size/configuration and extensive learning techniques, CAPEX can be brought down (IRENA and The Methanol Institute, 2021). For FT, higher OPEX can be due to the costs associated with catalyst development and regeneration, and the use of hydrogen for upgrading. Feedstocks such as MSW can be sourced at low cost, but may incur higher clean-up costs.

For pyrolysis, the CAPEX and OPEX components are comparable to those of gasification and FT. For a stand-alone bio-oil upgrading plant, CAPEX is very similar to that of a co-processing unit. However, the OPEX is lower for a co-processing unit since the process can be coupled to an existing petroleum refinery.

ATJ is another key technology that draws much interest. One benefit of the ATJ pathway could be the availability of ethanol as a mature biofuel. Using the right feedstock and process operation technologies, very high yields and energy efficiency can be achieved with ethanol production. Certain cases such as advanced fermentation may have higher costs for additional enzymes or catalysts required for pretreatment and hydrolysis steps. OPEX can also increase due to excessive heat requirements for steam distillation and dehydration of the produced alcohols. Production of alcohols from crops like sugarcane, corn and wheat requires the crops to be sourced sustainably without interfering with food production. With the recent fast-paced development towards commercialisation, CAPEX and OPEX for ATJ should decrease over time.

Catalytic hydrothermolysis and HTL could be a viable option, but they are still technologies with a low TRL. It would therefore be difficult to arrive at definite conclusions without a detailed techno-economic analysis of multiple such production facilities (and very few demonstration units exist currently).

As discussed throughout the report, the high cost of biojet fuel production, specifically the high CAPEX required, is probably the greatest barrier to its expansion. Although the price differential is influenced significantly by the price of crude oil, various groups have projected that, without policy support, it will take a long time or a major economic upset before biojet fuels become competitive with conventional jet fuels. However, as the various technologies become more fully commercialised, the price of biojet should fall.

Techno-economic comparisons have proven difficult to make when they are not based on the same assumptions. However, significant opportunities exist for cost reductions from optimisation. Several recent techno-economic analyses have indicated which components of the various biojet production processes are most sensitive to cost (Albrecht et al, 2017; Bann, 2017; Diederichs, 2015; Glisic, Pajnik and Orlović, 2016; de Jong, Hoefnagels, et al., 2017; Pearlson, 2011; Seber et al., 2014; Suresh, 2016; Yao et al., 2017; Zhu et al., 2014). HEFA and ATJ processes are particularly sensitive to feedstock cost, while gasification processes are most sensitive to capital cost.

Cost reduction opportunities include:

- The nature of the feedstock – e.g. feedstocks with high levels of contaminants will require more pretreatment and clean-up, adding to their cost and processing.

- Brownfield or greenfield construction of the facility – e.g. brownfield construction will reduce costs, with several HEFA renewable diesel facilities already based on the conversion/repurposing of disused or uneconomical refineries.

- Integration and/or co-location with existing facilities – e.g. significant cost savings can be achieved by integrating shared upstream or downstream infrastructure. As all drop-in biofuel technologies require hydrogen for upgrading, establishing dedicated hydrogen production would add significant infrastructure costs. By co-locating a biorefinery with an existing petrochemical facility containing a steam reformer or a hydrogen stream, significant capital cost savings should be achieved. Similarly, integration with a petroleum refinery for distillation/fractionation of products and utilising existing downstream transport and distribution infrastructure will be beneficial. Technologies based on biomass feedstocks could be integrated with a pulp, pellet or sawmill to enhance access to the feedstock supply chain and allow better utilisation of wastes/residues. A key area of integration is waste management, which has been shown to be a significant expense from a CAPEX and OPEX perspective.

- Feedstock costs – e.g. as feedstocks can account for 65-80% of OPEX when making HEFA-derived biofuels (Brown et al., 2020), sourcing cheaper feedstocks will make a significant difference. Although vegetable oil prices can vary quite significantly, with palm oil often among the cheapest, sustainability concerns will limit palm oil's use as a biofuel feedstock. Some palm oil may have worse carbon intensity than conventional jet fuel. Currently lipid feedstocks such as UCO and tallow tend to be cheaper, although they are in limited supply. As HEFA-based biofuel production increases, these feedstocks are likely become more expensive and difficult to source.

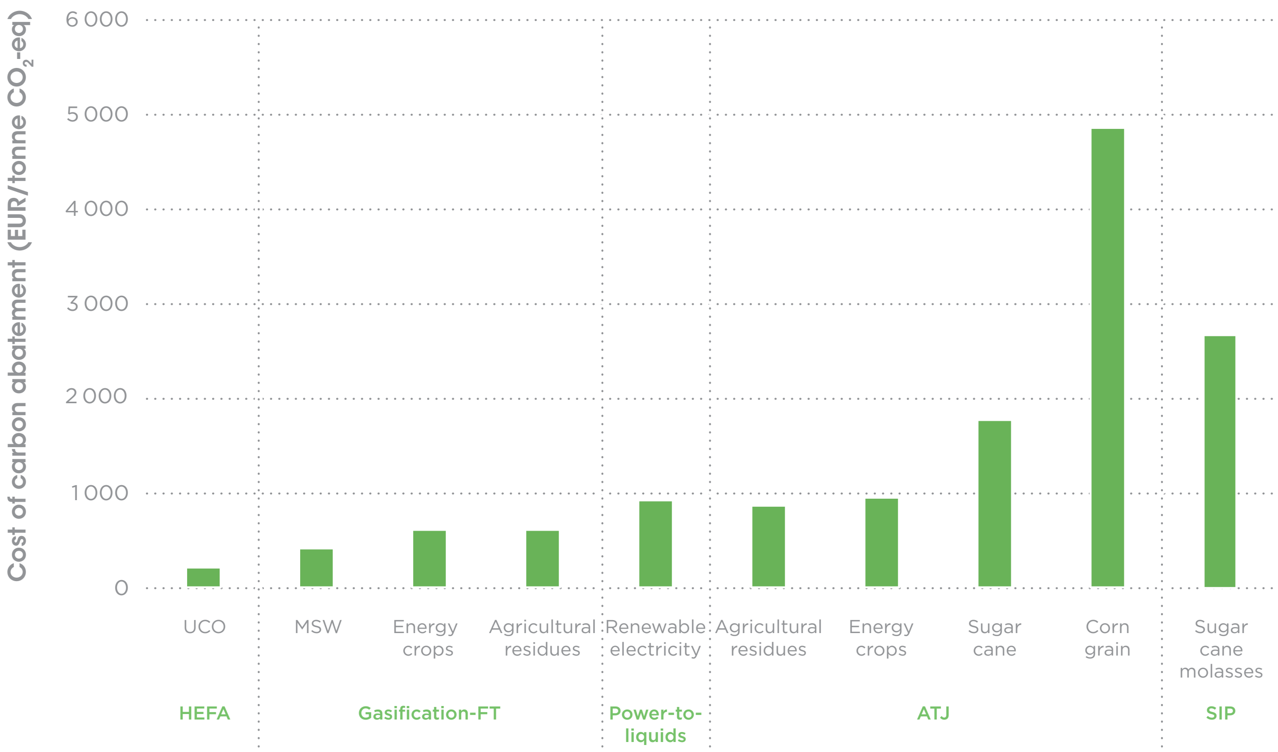
- Energy conversion efficiency and yields – e.g. as shown in many of the recent techno-economic analysis studies, theoretical conversion yields throughout the different steps of the process are often assumed. This is likely to result in an overestimation of yields (Albrecht et al., 2017; Bann, 2017; Diederichs, 2015; Glisic et al., 2016; de Jong, 2015; de Jong, Hoefnagels, et al., 2017; Pearlson, 2011; Seber et al., 2014; Suresh, 2016; Yao et al., 2017; Zhu et al., 2014). As HEFA-based processes are fully commercialised, they have available more reliable data to accurately determine overall yields. However, other still-evolving technologies such as gasification and FT generally report relatively low yields, which are significantly influenced by the nature of the feedstock, technology configuration, etc. (Snehesh and Dasappa, 2016). As several of the pyrolysis and HTL-type technologies are still in development, most studies have had to use estimates of yields. Biochemical-based technologies such as ATJ are heavily influenced by factors such as fermentation yields, with a significant impact on the projected overall economics (Geleynse et al., 2018).

- Maximising co-products – e.g. while this report is focused on biojet fuels, the production of other co-products, particularly those potentially with a high value, may have a significant beneficial impact on the cost of biojet fuel production.

Although the MFSP of biojet fuels is an important metric, it should not be considered in isolation of the broader "value" of the biojet. For example, the specific carbon intensity of the fuel will have an impact on the incentives available through policy and the extent to which offset obligations under CORSIA can be met. An alternative way of looking at cost is calculating the specific cost of carbon abatement, rather than just the MFSP, as this takes into account the price of the fuel and the price relative to the emission reductions offered. For example, a comparison of the carbon abatement cost of different biojet fuels shows that this is not a static metric (Figure 13). (Some of the available data on potential emission reductions for different technologies can also be found in Table 5.)

In summary, all of the "alternative" jet fuel technologies show substantially higher costs than conventional jet fuels (i.e. the baseline) and this is likely to remain the case in the medium to long term. However, each of the processes has considerable potential for cost reduction. In contrast to the generally accurate and reliable data available for HEFA-based biojet fuels, alternative pathways are based on estimates and assumptions from techno-economic analysis, which will vary by the time the technologies reach full commercialisation.

FIGURE 13. A comparison of the cost of carbon abatement for different biojet fuel technologies



Source: Searle et al. (2019).

Bridging the price difference between conventional jet and biojet fuels

As the price gap between conventional jet fuels and biojet fuels is currently restricting the expansion of biojet fuel, here are ways in which this price gap might be "managed":

1. The airline could purchase the biojet fuel at a higher price and increase the cost of tickets to cover the increased fuel cost. At low blends (5%), this may only be a small amount per passenger.

2. Airlines may purchase the biojet fuel and give passengers the option to voluntarily add a further fee to the ticket price to cover the cost of the biojet fuel or to offset the emissions associated with their flight as determined by a carbon calculator. Alternatively, passengers may opt to pay a lump sum regardless of the specific emissions associated with their flight.

3. Airports may also offer initiatives to bridge the price gap. For example, reducing landing fees for airlines using biojet fuels or using other airport fees to contribute to the price difference.

From an airline perspective, policies that "level the playing field" between airlines are preferred. For this reason, the greatest impact on biojet fuel growth will undoubtedly be policies that directly promote or mandate increased production, such as producer and blender incentives. Related policies that reduce the financial risk for investors through mechanisms such as loan guarantees and grants for construction of facilities would also directly help enhance biojet fuel production.

8. ENSURING THE SUSTAINABILITY OF BIOJET FUELS

As discussed earlier, the primary motivation for developing biojet fuels is to reduce the carbon footprint of the aviation sector. Thus, ensuring the overall sustainability of biojet production and use will be a critical component of its development. Overall sustainability is typically assessed by certification bodies who consider the complete supply chain against a number of principles and criteria. Two prominent certification bodies that have been involved in the assessment of the sustainability of biojet fuels are the Roundtable on Sustainable Biomaterials (RSB)[14] and International Sustainability and Carbon Certification (ISCC).[15] Other organisations such as the Programme for the Endorsement of Forest Certification (PEFC), the Sustainable Forest Initiative (SFI),[16] the Forest Stewardship Council (FSC)[17] and the Sustainable Biomass Program (SBP)[18] are arms-length certification systems specifically designed to assess the sustainability of forestry-based feedstocks and forestry practices and to ensure that woody biomass is sourced from legal and sustainable sources. Organisations such as the Roundtable on Sustainable Palm Oil and the Roundtable on Sustainable Soy set standards for these specific feedstocks.

As mentioned earlier, the need to lower greenhouse gas emissions has been recognised by ICAO, with ICAO member states setting ambitious targets to mitigate them. CORSIA was established by ICAO to achieve carbon-neutral growth from 2020 and to address the increase in total CO_2 emissions resulting from aviation. While a core element of CORSIA is the purchase of offsets to meet these obligations, airlines can also meet the requirements of CORSIA through the use of sustainable aviation fuels.

CORSIA submitted a description of the criteria that should be used to assess the eligibility of biojet fuel/ sustainable aviation fuel to the ICAO council in 2016. To be eligible a fuel should generate lower carbon

14 https://rsb.org/.

15 www.iscc-system.org/.

16 www.sfiprogram.org/.

17 https://fsc.org/en.

18 https://sbp-cert.org/.

emissions, on a life-cycle basis, and not be made from biomass obtained from land with high carbon stock. Other criteria include:[19]

- At least 10% net greenhouse gas emission reductions compared to the baseline life-cycle emission values for aviation fuel on a life-cycle basis.
- No land-use change on land with high carbon stock (primary forests, wetlands and peatlands) on or after 1 January 2008.

Although CORSIA is likely to develop additional sustainability criteria in due course, CORSIA has already approved other certification bodies such as the RSB to verify the sustainability of biojet fuels. It should be noted that the RSB sustainability criteria are more comprehensive than the current CORSIA criteria (RSB, 2016).

As the emission reduction potential of biojet fuel is a central part of its sustainability, it is typically determined via the life-cycle assessment (LCA) of a biojet fuel supply chain as compared to the emissions from using conventional jet fuel. Thus, every feedstock/technology supply chain will have a different carbon intensity. Although CORSIA has determined default carbon intensities for several pathways of biojet fuel production, it is likely that a biofuel production company will have to carry out a full LCA to obtain a specific value for their biojet fuel pathway.

The carbon intensity of biojet fuels and potential emission reductions

While significant emission reductions are possible when using biojet fuels, every feedstock/technology pathway will have a unique carbon intensity[20] for the finished fuel. Several factors will affect the actual carbon intensity of the biojet fuel. These include the nature of the biomass feedstock, agricultural practices used (e.g. no till, fertiliser usage) and harvest yields, as well as technological factors such as the source of electricity/hydrogen, total product yields, amount and nature of the co-products and waste water treatment.

Although initiatives such as CORSIA (ICAO, 2019d), or the EU's Renewable Energy Directive (RED) have established default values for feedstock/technology pathways, the carbon intensity of an overall process and product is not static (Table 5). For example, companies can drastically reduce the carbon intensity of fuels by several mechanisms, such as improving the feedstock supply chain or decarbonising the conversion process. Using hydroelectricity rather than coal-derived electricity can have a significant impact (Ringsred, 2018).

19 www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-FAQs.aspx.

20 Expressed as g CO_2-eq/unit of energy in megajoules (MJ) or British thermal units (BTU).

TABLE 5. ICAO default life-cycle emissions for CORSIA-eligible fuels

Fuel conversion process	Region	Fuel feedstock	LSf (g CO_2-eq/MJ) (core LCA plus ILUC)
FT	Global	Agricultural residues	7.7
	Global	Forestry residues	8.3
	Global	MSW (0% NBC)	5.2
	Global	MSW (NBC as a %)	NBC*170.5+5.2
	USA	Poplar	7.0
	USA	Miscanthus	-22.5
	EU	Miscanthus	-11.6
	USA	Switchgrass	6.6
HEFA	Global	Tallow	22.5
	Global	UCO	13.9
	Global	Palm fatty acid distillate	20.7
	Global	Corn oil (dry mill ethanol plant)	17.2
	USA	Soybean oil	64.9
	Brazil	Soybean oil	67.4
	EU	Rapeseed oil	71.5
	Malaysia and Indonesia	Palm oil – closed pond	76.5
	Malaysia and Indonesia	Palm oil – open pond	99.1
ATJ (isobutanol)	Global	Agricultural residues	29.3
	Global	Forestry residues	23.8
	Brazil	Sugarcane	31.3
	USA	Corn grain	77.9
	USA	Miscanthus	-10.7
	EU	Miscanthus	12.4
	USA	Switchgrass	28.9
ATJ (ethanol)	Brazil	Sugarcane	32.8
	USA	Corn grain	90.8
SIP	Brazil	Sugarcane	32.8
	EU	Sugarbeet	52.6

Notes: g = gram; ILUC = indirect land-use change; LSf = life-cycle emission factor under CORSIA; NBC = non-biogenic carbon.

Source: ICAO (2019d).

Possible strategies to further decrease the carbon intensity of biojet fuels

As discussed, the carbon intensity of biojet fuels can vary widely depending on the nature of the feedstock, technology and so on. Recent work has shown how the carbon intensity of biojet fuels can be further reduced, including the following:

- The energy source can be changed from fossil-based to renewable (hydro, wind, solar, etc.). This strategy has been successfully used by Gevo to reduce the carbon intensity of its isobutanol production (Gevo, n.d. b).

- Changing the source of hydrogen from natural gas to renewable sources such as biogas, or produced with electrolysis of water from renewable electricity (de Jong, Antonissen, et al., 2017).

- Increasing the number of co-products so that the carbon emissions are allocated to all products, according to their energy or value (Mahbub et al., 2019).

- Including integrated waste management strategies for waste that would otherwise be disposed of. Many wastes are a source of methane that will be included in the LCA. For example, palm oil production with integrated waste management has a significantly lower carbon intensity when anaerobic digestion is used to treat waste materials (Hansen, Olsen and Ujang, 2012).

- Reducing emissions in the feedstock supply chain. For example, encouraging farmers to practice no-till methods. This is used by Gevo to help improve the carbon intensity of its isobutanol production.

- Including carbon capture and storage processes at the biofuel facility (de Jong, Antonissen, et al., 2017).

9. CHALLENGES LIMITING BIOJET FUEL PRODUCTION

Deep reductions in aviation emissions by 2050 imply that substantial amounts of biojet fuel will be required. Significant challenges will be encountered trying to achieve these biojet volumes.

Potential feedstock supply and challenges

Multiple feedstocks can be used to produce biojet fuels, including lipids (vegetable oils, UCO and other waste lipids), starches, sugars and lignocellulosics (forest residues, agricultural residues and energy crops). Theoretical feedstock availability is not expected to be a barrier to biojet production, although high prices may be a barrier. The challenge relating to feedstock is rather the competing uses for other applications, such as bioenergy for heat and electricity, and availability once these have been satisfied. The cost of feedstock can be a significant obstacle and biojet fuel production is very sensitive to the cost and sustainability of feedstock. The low energy density of lignocellulosic feedstocks such as forest residues makes transport cost an important factor, and feedstock can only be transported economically over limited distances.

Staples et al. conducted a comprehensive analysis of feedstock availability, with a maximum feedstock availability at 510 EJ/yr, a minimum availability at 41 EJ/yr, and an intermediate baseline estimate of 178.7 EJ/yr (Staples et al., 2018). Parameters that affect the calculations include the agro-climatic suitability threshold (effect of climate change), feedstock crop yields, land use change emissions thresholds and so on. If all feedstocks (minimum to maximum availability) are directed towards biojet fuel production (ignoring competing uses and cost of feedstock), between 34.4 EJ/yr and 201.9 EJ/yr of biojet fuel could be produced. At the lowest feedstock availability scenario, about 90% of jet fuel demand can be met if all feedstocks are allocated to biojet production.

Taking a global perspective, the potential for sustainable biomass in 2030 has been estimated at 97-147 EJ/y (based on total minimum and total maximum scenarios) (IRENA, 2014). However, there is substantial potential to sustainably expand the bioenergy supply (IRENA, 2016b).

Waste and residues from forestry and agriculture have greater availability and would represent the bulk of the raw materials for advanced biofuels. So-called energy crops can also be grown, preferably on land that is not used for food or other crops, such as contaminated and marginal land (IRENA and The Methanol Institute, 2021).

To be sustainable, these crops would also have to comply with a number of other criteria, including impact on soil quality, soil erosion, need for water and fertilisers, biodiversity concerns, land tenure and emission of pollutants to air and water.

When the price of the feedstocks and competing uses are taken into account, the picture changes dramatically. Where biojet production has the lowest priority compared with other applications, no biojet fuel is produced in any scenario (Staples et al., 2018). This highlights the significant role of policy in the agricultural sector to influence feedstock supply for biojet fuel production**.**

Although initial biojet supply chains will be based on oleochemical/lipid feedstocks, biodiesel and renewable diesel use the same lipid feedstocks as HEFA biojet. These low-carbon-intensity diesel fuels are much easier and cheaper to produce, plus renewable/biodiesel production is an established, commercial process with policies such as mandates already in place in many jurisdictions around the world. At the same time, as biomass-based biojet technologies mature, there will be increasing competition for the biomass feedstock, which can be used as bioenergy for heat and power generation as well as other biofuels that can be used in road, rail and marine transport.

As opposed to some of the end-use sectors/applications that have alternative ways of reducing their emissions, such as using "green" electricity, aviation is heavily reliant on biojet fuels if it is to be decarbonised. Thus, there is a need to establish specific policies that encourage the use of feedstocks to make biojet fuels rather than for other applications that might be cheaper, less technically challenging and which also result in substantial carbon reductions. As discussed, the potential volume of biojet fuel will depend significantly on preferential allocation of feedstocks.

As demonstrated by companies such as Neste and specific policy drivers such as California and British Columbia's LCFS, "waste" lipids such as FOGs – including UCO and tallow – are in high demand primarily because of the low carbon intensity of these feedstocks (Bonomi, Klein and Chagas, 2018). However, the limited supply of these feedstocks means there will be increasing use of vegetable oils such as rape, soya and sunflower, with the carbon intensity of their production coming under increasing scrutiny. Although alternative lipid feedstocks, such as camelina, carinata, jatropha and salicornia, are in development, they are unlikely to provide the needed volumes in the short to medium term. While palm has very high oil yields per hectare, ongoing concerns about sustainability continue to limit its use and potential as biofuel feedstock (Transport & Environment, 2018).

For all of the oleochemical/lipid-based HVO/HEFA routes to biofuels, including biojet fuel, the technologies are relatively mature. Thus, the relatively high cost of the feedstock is the major economic challenge that needs to be overcome.

In the longer term, it is hoped that biomass-based technologies will provide cheaper, more abundant and lower-carbon-intensity biojet fuels, particularly if the feedstocks are recognised as wastes. Although biomass-based biojet fuel processes are currently more of a technological rather than a feedstock challenge, as indicated earlier, increasing competition for biomass feedstocks can also be anticipated.

The availability of forest residues is closely linked to forestry activities for higher-value products, such as lumber, as using whole trees will not be sustainable or economical for biojet fuel applications under most circumstances. Although some residues are currently used for products such as wood pellet production, supply chains are not generally in place and would have to be established from scratch. Supply chain optimisation will be closely linked to the cost of the feedstock and its economic utilisation for biojet fuels. There is, furthermore, already significant competition as residues are used extensively for heat and power production. Wood pellets are exported from North America to the European Union for biomass power stations and thus biojet fuel production will have to compete with these applications. Agricultural residues have been used to some extent in cellulosic ethanol production facilities, but in general these supply chains are not developed. The inability of such facilities to stay in business has been closely linked to feedstock characteristics and supply. Agricultural residues are only available on a seasonal basis and a biorefinery has to engage in individual contracts with farmers and develop its own supply chains and storage (also essential to establish sustainability along the supply chain).

Many other feedstocks, such as energy crops (e.g. miscanthus) that are usually included in feedstock availability estimates, are not commercially grown and their availability will rely on their commercial development. This also emphasises the importance of feedstock readiness, as opposed to technology readiness, as an essential component in the commercialisation of biojet production.

Challenges with respect to the rate of technology commercialisation

HEFA technology is currently the only fully commercial pathway and other technologies are at different TRLs. Therefore the rate of technology commercialisation will play a significant role in the overall expansion and commercialisation of biojet fuel production. Note that commercialisation is defined as multiple facilities of the same technology operating at or near capacity.

The progression of biofuel technology from one TRL level to the next has been very slow and estimated at 3-5 years per TRL level (Mawhood et al., 2016). In addition, commissioning and ramping up a newly constructed facility can take up to five years. As an example, the gasification with FT synthesis pathway based on biomass received ASTM certification in 2009, but the first pioneer commercial-scale facilities are only currently under construction.

In the absence of stable supportive policies to mitigate risk over the long term, a biojet refinery poses a high risk to investors, particularly when the failure of some recent biofuel facilities is considered (Fehrenbacher, 2015).

For technologies that have yet to receive ASTM certification, such as pyrolysis or hydrothermal liquefaction, a further challenge is the lengthy and costly process involved in achieving ASTM certification.

The challenge of significant capital investment costs

Capital costs vary significantly between different technologies. This report found them to range between USD 129 and USD 1 100 per tonne of fuel based on the average capital cost of each technology group (see Annex B). At the lower end of the range is HEFA/HVO technology, which is already mature and well commercialised. However, the increasing demand for biojet in the future and limited availability of lipid feedstock will require a wider range of other technologies that have a higher investment cost.

IRENA's 1.5°C Scenario (1.5-S) , which has a goal of holding the global temperature rise to no more than 1.5°C, estimates that about 200 billion litres of biojet fuel will be required per year. This will involve approximate USD 5 billion of investment costs per year until 2050.

According to analysis by ICAO, linear growth in capacity to provide enough biojet for the complete replacement of conventional jet fuel for international flights would require approximately 170 large new bio-refineries to be built every year from 2020 to 2050 at an approximate capital cost of USD 15 billion to USD 60 billion per year (ICAO, 2019a).

The complete study was published by Staples and shows in detail multiple scenarios based on the availability, cost and allocation of feedstock to different renewable energy applications (Staples et al., 2018) (see Table 6 for four of these scenarios).

TABLE 6. Selected sustainable aviation fuel scenarios based on all technologies and the corresponding number of biorefineries required and anticipated annual capital investment

Achievement scenario	Production volume in 2050 (Mt/yr)	No. of biorefineries in 2050	New biorefineries per year (2020-2050)	Capital investment per year (2020-2050) (billion USD_{2015}/yr)
S2A3F2	30.2	286	9	0.7-2.8
S2A2F2	133.1	1 262	41	3.4-13.4
S2A1F2	349.9	3 317	110	9.0-35.9
S2A1F1	850.3	8 061	268	21.9-87.6

Note: It is assumed that the biojet fraction is 50% of each biorefinery's total fuel production.

Scenarios: **S2** = 178.7 EJ/yr of feedstock availability (an intermediate scenario).
A1 = feedstock cost of USD 1/GJ; **A2** = feedstock cost at USD 2/GJ; **A3** = feedstock cost at USD 4/GJ.
F1 = maximum feedstock going to jet production; **F2** = proportional allocation of feedstock to multiple applications; **F3** = feedstock used for other applications first.

Source: Staples et al. (2018).

Regulatory challenges to biojet production – the need for effective policies

The majority of the world's successful biofuel policies have focused on "conventional" biofuels (ethanol, bio/renewable diesel) and have mostly been based on volumetric mandates that did not specify minimum carbon emission reductions (Lane, 2018). Although a few policies have tried to promote the production and use of advanced/drop-in biofuels, overall there is a dearth of assertive and stable policies to promote drop-in biofuels and biojet fuels in particular (Lane, 2018).

The regulation of international aviation is unique and based on bi- or multilateral agreements between countries. At an international level, negotiations for a market-based mechanism (CORSIA) took a long time, with progressive implementation dates meaning some airlines will only begin offsetting after 2027. Although domestic aviation emissions could be regulated nationally, the sector has, to a large extent, "fallen through the cracks". As discussed earlier, although CORSIA provides motivation, it is likely to have limited impact on biojet fuel development, with the onus on biojet/lower-carbon-intensive jet fuel developers to bring these fuels to market.

Some jurisdictions have developed policies to address aviation emissions, such as the EU Emissions Trading System, which governs about 40% of all EU greenhouse gas emissions (including power and heat production, cement production, iron and steel production and oil refining) (European Commission, n.d. a). However, it is only applicable to flights within the European Union and does not apply to international flights. Other jurisdictions have developed related initiatives such as green taxes and support for biojet development (GreenAironline, 2020).

10. POLICIES TO INCREASE BIOJET FUEL PRODUCTION AND USE

Ambitious, stable and internationally relevant policies will be needed if there is to be a significant increase in biojet fuel production and use. Several recent reports have assessed the types of policies that will be required to increase biojet fuel production and use (World Economic Forum, 2020).

Such policies will need to address factors such as unfavourable economics, limited feedstock availability, competition from other low-carbon fuel uses and immature technologies, which currently limit the use of sustainable aviation fuel, including biojet. If the aspirational 2050 carbon reduction targets of the sector are to be met, the construction and repurposing of hundreds of facilities will be needed, requiring hundreds of billions of dollars of investment. These facilities will then produce the low-carbon jet and other low-carbon fuels via many of the production pathways discussed in this report (Staples et al., 2018). Effective policies will also be required to catalyse many of the components of viable supply chains, from the production of low-cost and sustainably derived feedstocks through to the preferential production and use of low-carbon-intensive jet fuels. Aviation may compete with other modes of transport (e.g. cars, trucks, ships and trains) for similar fuels as they all seek to decarbonise.

Domestic aviation typically falls under national laws and regulations and forms part of a country's nationally determined contributions under the Paris Agreement. International aviation falls under ICAO jurisdiction and is likely to be more difficult to enforce (ICAO, 2020d). This "dual policy system" will likely place additional administrative burdens on airlines and could result in anomalies. For example, the CORSIA offsetting scheme applies to international flights, while national carbon/fuel taxes may apply to domestic flights according to local regulations. Emissions at the domestic level cannot also be used under CORSIA, so as to avoid potential double counting, and this has to be verified by verification bodies approved under CORSIA. At a national level, the policies that have successfully promoted the use of biofuels for road transport, such as renewable diesel, have probably resulted in a competitive advantage for this particular transport mode, to the detriment of encouraging biojet fuel development.

WHAT IS A LOW-CARBON FUEL STANDARD?

A LCFS is designed to encourage the use of low-carbon transport fuels. A declining target or benchmark carbon intensity is established that compels providers of transport fuels to supply fuel that meet this obligation. Low-carbon fuels below the benchmark generate credits, while fuels above the benchmark generate deficits.

The carbon intensity is determined according to an LCA of the entire fuel production pathway, covering direct and indirect effects.

Over each annual compliance period, the fuel provider must meet its obligations by blending with biofuels, or through the purchase of credits from other parties.

The LCFS is technology-agnostic.

Policy drivers

Biofuel policies can generally be divided into two broad categories of "technology push" and "market pull". These policies are complementary and act in different ways to promote biofuel production and market development. A combination of both types of policies will be essential if there is to be a significant increase in biojet production and use. While market pull policies are critical for biofuels expansion, the use of mandates for biojet fuels may be considered premature as commercial volumes of biojet fuels are currently limited. Demand may be driven up by passenger willingness to pay a higher price for tickets to reduce their carbon footprint. As discussed below, it is more likely that, under current conditions, a mandate will promote existing commercial technologies, such as HEFA, to the detriment of other developing technologies. As a result, technology push policies will also be required to help construct new facilities and overcome research challenges, for example via loan guarantees and research grants. Thus, a significant focus on technology push policies will be needed (Costantini et al., 2015).

Advanced technologies and pathways will also need to be scaled up if we are to attain the sector's aspirational carbon reduction goals. As conventional biofuels (e.g. bioethanol/biodiesel) can be considered to be relatively mature, their production and use has primarily been promoted by market pull policies such as mandates and quotas. However, a similar policy approach is unlikely to be as effective in encouraging the production and use of advanced biojet fuels as many of the technologies are not yet mature.

In the shorter term, it is likely that market pull, price-based policies that offer stability and security to investors will have a more significant impact than quantity-based policies such as mandates or quotas. Unlike road transport, where the production and use of lower-carbon-intensive fuels have been driven by governments, the desire for lower-carbon-intensive aviation fuel has come from airlines, their customers and original equipment manufacturers (such as Boeing and Airbus) looking for ways to decarbonise while staying economically viable. As a result, the aviation sector has been supporting biojet fuel development in several ways, for example, by significant investment in biojet fuel production facilities, long-term offtake agreements (Csonka, 2020), and supporting research initiatives such as the Aviation Sustainability Centre (ASCENT). Similar initiatives in Europe include Flightpath, aireg, Bio4A, Jetscreen and Flexjet.

Due to the significant difference in price between biojet and regular jet fuel, effective price-based market pull policies will play a much more important role than they did in establishing conventional biofuels such as bioethanol/biodiesel. These types of policies will complement the technology push policies used to improve investment in current and future biojet fuel production facilities. However, as the processes used to make biojet fuel tend to be more complex and require higher capital investment than the production of conventional biofuels, any grants or loan guarantees for the construction of biojet-specific facilities will have to factor in the higher CAPEX required to build them.

Where market pull policies such as mandates are used (e.g. in Sweden and Norway), they should be linked to emission reduction targets, such as those used in LCFSs, rather than merely establishing volumetric fuel targets where the actual carbon intensity of the biojet fuel is less important.

In addition, the current LCFS-type policies that have been used to decarbonise road transport can be expanded to include biojet (and marine fuels), as an opt-in. This would allow these fuels to earn credits without incurring debits under the system, and would incentivise biojet production without setting compliance targets for emission reductions, given that biojet availability is limited. It is also very likely that a "fuel multiplier" for biojet fuels would have to be incorporated into these types of policies. This would allow biojet fuels to earn more credits as compared to a similar volume of renewable diesel and help bridge the greater investment required to make biojet fuels.

WHAT IS MEANT BY AN OPT-IN?

A policy such as the LCFS in California regulates specific fuels, including gasoline, diesel and substitutes or blendstocks. Some fuels are not regulated under the LCFS, such as biojet fuel, but fuel providers can apply to voluntarily opt into the programme in order to generate credits that they can sell and trade in the California LCFS market.

Aviation was included in the California LCFS in September 2018.

Policies to encourage the production and use of drop-in biofuels

While more than 60 countries have some form of biofuel blending mandate or obligation policies to promote the production and use of bioethanol and biodiesel, so-called "drop-in" biofuels have been faced with particularly difficult challenges.

Under these mandates and policies, the lower-carbon fuels that have been produced have generally been used in limited blends (except for Brazil where flex-fuel vehicles dominate the car market). The blend wall is a major impediment to significant carbon emission reductions in the transport sector. In contrast, drop-in biofuels can typically be used as a 100% replacement for gasoline and diesel, resulting in significant emission reductions. Given that several economic challenges remain for the scale-up of drop-in biofuels, such as high feedstock and upgrading costs, future policies will likely have to provide enhanced support for their production and use (e.g. larger grants and higher incentives/subsidies). Such policy support would set the transport sector, including aviation, on a pathway to the decarbonisation.

Emissions from domestic and international aviation currently fall under different jurisdictions

As domestic and international aviation policies currently fall under different frameworks, it would be highly beneficial if these policies were better integrated. For example, the Chicago Convention and resulting bilateral agreements between countries prohibit the application of fuel taxes on international flights. Consequently, although reducing fuel taxes has been successfully used to promote the consumption of biofuels for road transport such as bioethanol and biodiesel, this strategy is not workable for international aviation. This is further compounded by the CORSIA agreement only applying to international aviation, with offsetting requirements just applied to growth in international aviation. As about 80% of CO_2-eq emissions come from flights of over 1 500 km, international flights contribute significantly to emissions (ATAG, 2020). However, it is likely to be easier initially to develop policies for domestic aviation, by adapting the policies that have been successfully used to incentivise the production and use of fuels for land transport. For example, California has allowed the opt-in of biojet fuels into its LCFS.

Policies and programmes that have been used to develop feedstock and supply chains

Policies such as the Biomass Crop Assistance Program (USDA, n.d. b) and the Farm-to-Fleet Program (a joint USDA and US Navy programme) (USDA, n.d. c) have incentivised feedstock development and have been an integral part of conventional biofuels development in the United States. Thus, it is highly likely that similar policies that support the research and development of sustainable and waste feedstocks will be a key component of any future biojet fuel development. For example, the USDA billion-ton report and subsequent updates involved a nationwide assessment of feedstock availability in the United States for the potential production of biofuels (US DOE, 2016). Similar studies could provide the basis for potential biojet fuel supply chain development, based on regional conditions. Feedstock development can also create jobs and boost the economy in rural communities. Similar to current employment in the biofuel sector, most of these jobs are expected to be in feedstock supply, such as the agricultural sector. Currently, employment in the biofuel sector stands at about 2.5 million (IRENA, 2020b).

Using a multiplier to encourage the production and use of biojet fuels rather than their use for road transport

Although biofuel policies have been implemented in many countries, they have almost exclusively focused on road transport. In the few cases where aviation has been addressed, any biofuel-related incentives have not differentiated road and air transport, with this competition resulting in the majority of the biofuel being used for road transport as it is usually easier to produce.

Some jurisdictions have tried to address this imbalance by introducing "multiplier" policies, which increase the incentives earned when producing biojet fuels (Sustainable Aviation, 2020). In these cases, the biojet fuel earns a higher credit or incentive than a similar volume or energy content of an alternative fuel such as renewable diesel. This enhances the value of the biojet fuel, which improves its competitiveness against renewable diesel (Ghatala, 2020).

However, some groups have suggested that the multiplier should not be more than 1.2, as a higher multiplier might lead to inefficiencies in biojet fuel production (Bitnere and Searle, 2017). In most cases, biojet fuels are produced as one component of a fuel blend that contains multiple products such as light gases, gasoline, naphtha, diesel, heavy fuel oil and waxes. Although the jet fraction can be increased by additional processing such as hydrocracking, to break long waxes and diesel molecules into smaller jet-range hydrocarbons, it also creates shorter hydrocarbons such as naphtha and gases. These fractions have a lower value, while the overall yield of liquid fuel is also reduced. The hydrocracking step also comes at an additional cost to the refinery. Thus, if the value of the jet fuel is artificially increased through a multiplier higher than 1.2, the overall refinery operations will be impacted. Although the biojet fraction is automatically produced during the production of renewable diesel, a distillation step is typically required to separate out the biojet fraction.

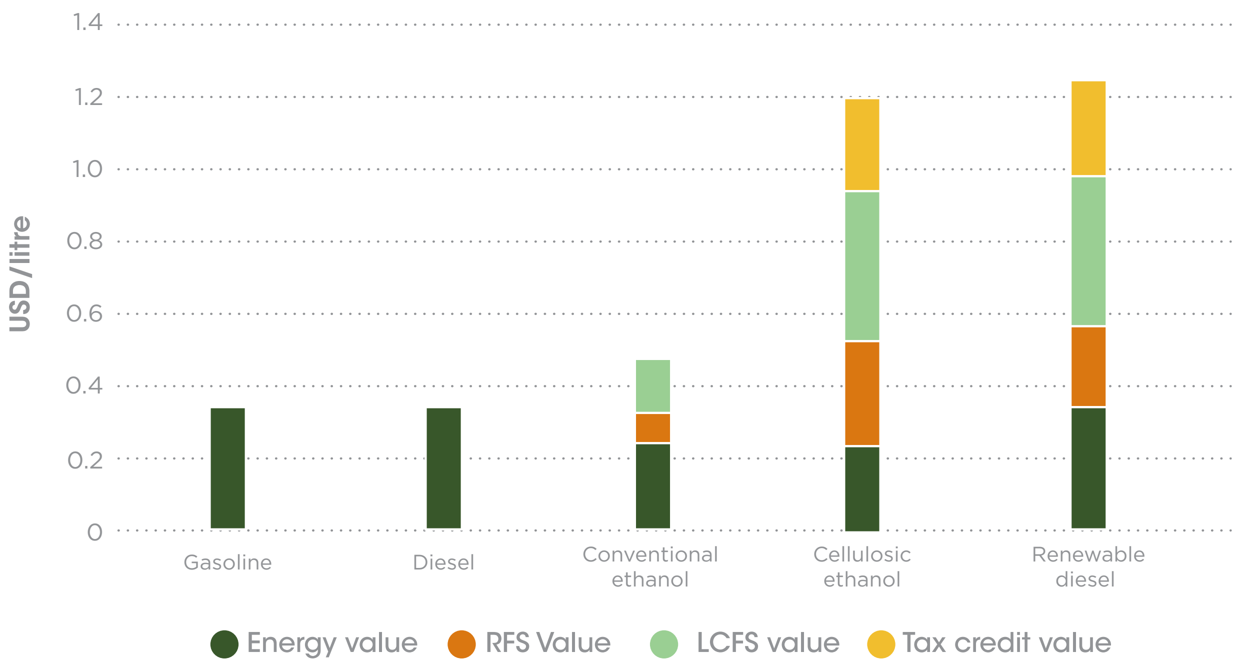
It is worth noting that, if renewable diesel facilities were incentivised to do so, about 15% of the total renewable diesel refinery capacity could be available for biojet fuel production. Based on the current global renewable diesel capacity of 6.5 billion litres (still expanding), this would amount to an immediate volume of 1 billion litres of biojet fuel being available. The only requirement would be some additional capital investment in the distillation step used to facilitate biojet fuel fractionation. Consequently, it is possible that a "multiplier" policy could encourage a fairly rapid increase in biojet fuel production, if this policy was in place for a sufficient time period to ensure an adequate return on investment.

Possible financial incentives, tax credits and exemptions

Incentives or subsidies, such as producer or blender tax credits, have played a significant role in encouraging investment and the development of conventional biofuels (CBSCI, 2019). Some groups have suggested that producer incentives will be less important at stimulating drop-in and biojet fuel production due to the higher capital investment costs compared to conventional biofuels (Searle et al., 2019).

However, it is likely that biojet fuel production would still benefit from these types of incentive, as loan guarantees and grants could play an important role in encouraging initial investment in drop-in biofuel/biojet fuel facilities. Other policies, such as producer incentives, would mitigate the longer-term risk to investors, with the information in Figure 14 illustrating the impact of incentives on five different transport fuels under the California LCFS (Lane, 2020). The current situation in California with respect to biofuel incentives and their impact on the value of the biofuel shows that conventional ethanol, cellulosic ethanol and renewable diesel can earn incentives under the federal Renewable Fuel Standard (orange), as well as LCFS credits under California's policies (light green), while the two advanced biofuels (cellulosic ethanol and renewable diesel) can also earn further federal tax credits (yellow).

FIGURE 14. Illustration of incentives for various fuels in California under state and federal law



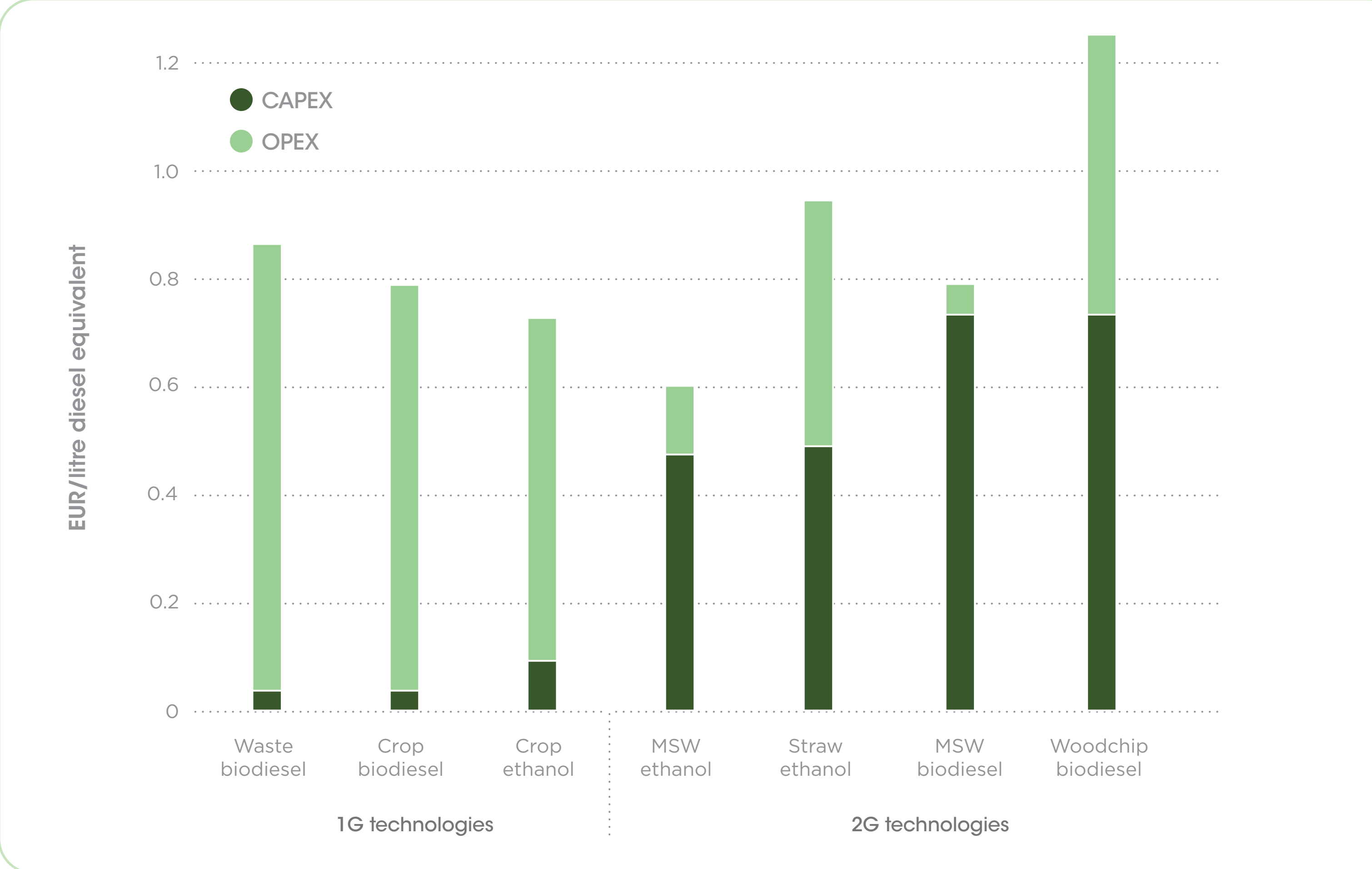
Source: Lane (2020).

Grants and loan guarantees must reflect higher investment cost of drop-in biofuels

As discussed, achieving the aviation sector's aspirational carbon reduction targets will require the investment of several trillions of dollars over the next 30 years (Staples et al., 2018). The capital investment required to produce drop-in biofuels is much higher than a similarly sized bioethanol and biodiesel facility (Bitnere and Searle, 2017). This is mostly due to the increased complexity of making drop-in biofuels, which typically includes processing steps such as catalytic cracking, hydrotreating and distillation. As a result, strong technology push policies will be required to drive investment, with grant and loan guarantees needed to accelerate the construction of these facilities. As the lifetime of these projects could range from 15 to 25 years, investors will want policy certainty to ensure a guaranteed return on investment (Bitnere and Searle, 2017). As summarised in Figure 15, different types of biofuel technology have significant differences in CAPEX and OPEX, specifically highlighting the difference between first-generation (conventional) and second-generation (advanced) technologies (Bitnere and Searle, 2017). The CAPEX for second-generation technologies is typically considerably higher than for first-generation technologies such as sugar/starch ethanol and biodiesel.

Related work (Figure 16) summarises the capital costs of different advanced fuel technologies while also making a distinction between feedstock costs and other operational costs. In other studies the feedstock costs are typically incorporated in the operational costs.

FIGURE 15. Comparison of CAPEX and OPEX for various biofuel technologies



Source: Bitnere and Searle (2017).

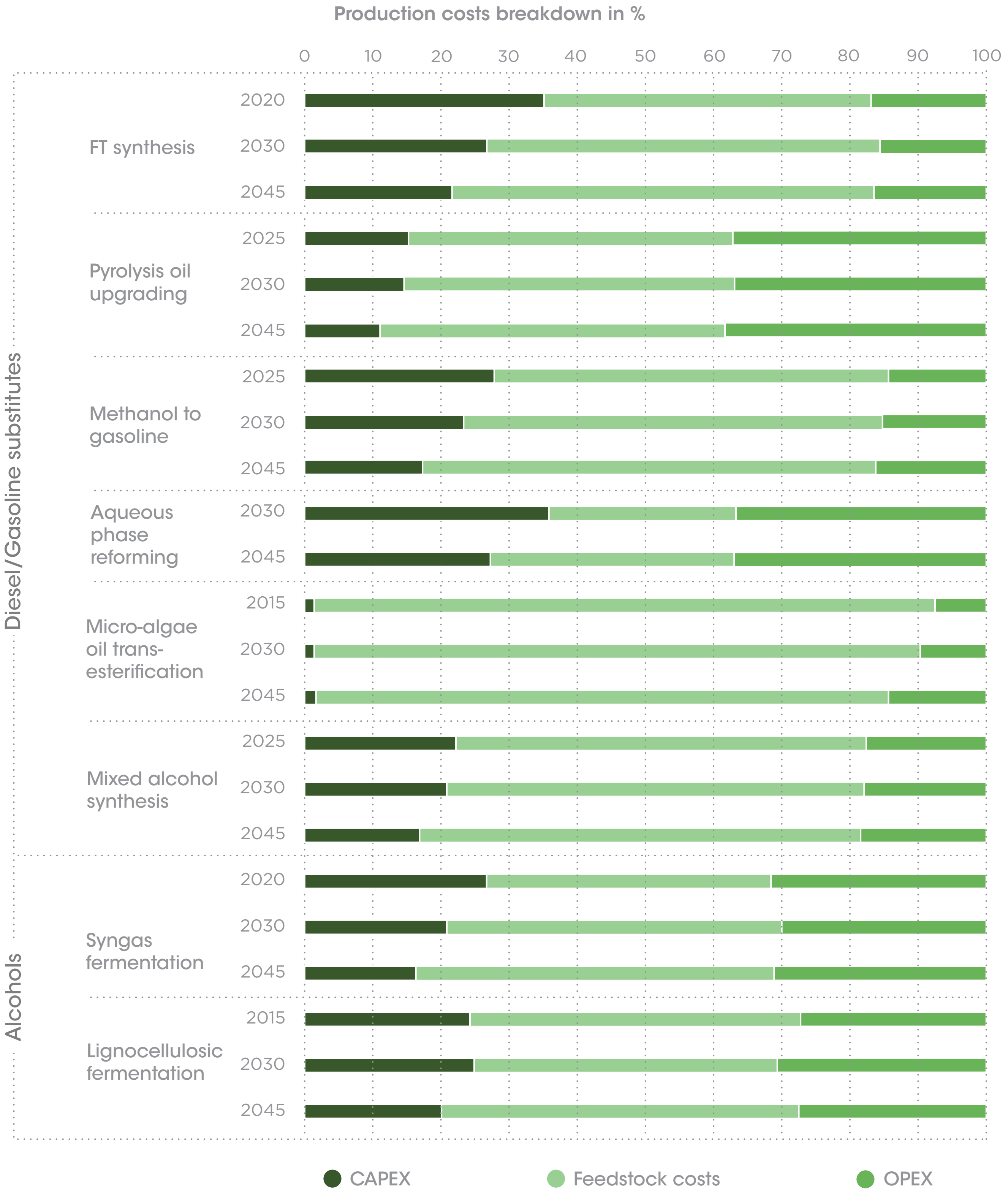
Price guarantees and contracts

Observers recognise that "dedicated incentives… with a clear, predictable value to producers" will be important in developing advanced biofuel policies (Searle et al., 2019), with the establishment of "contract for difference" mechanisms ensuring investor certainty (Pavlenko, Searle and Nelson, 2017). This type of programme would establish a guaranteed price floor to maintain the same profit margin for biofuel producers regardless of fuel prices or the value of incentives/subsidies (Searle et al., 2019). As the price gap between conventional jet fuel and biojet fuel is probably the most significant barrier to biojet development, some form of price guarantee could be an effective policy in helping mitigate the risk for investors.

The potential to use taxes and fees to promote biojet fuels

Although current international agreements limit the taxing of jet fuel for international flights, policies such as green taxes or environmental levies on passengers have and are being used as a mechanism to decarbonise aviation in several countries. For example, in 2018 Sweden introduced an air travel tax on all passengers, with the amount varying depending on the distance travelled (McDermott, 2018). Although the major objective of the tax was to reduce the carbon footprint of flying, it also motivated passengers to consider more environmentally friendly methods of transport such as rail. Similar taxes have been implemented in France (Euractive, 2019), Italy and Norway, with the Netherlands

FIGURE 16. Breakdown of relative production cost for different advanced biofuel technologies divided into capital cost, feedstock cost and operational cost



Source: IRENA (2016a).

introducing a similar levy on passengers from 2021 prior to a pan-European tax possibly being implemented (Morgan, 2019). Recent announcements have indicated that France will use this revenue to fund other forms of low-carbon transport (Stokel-Walker, 2019).

However, some groups have claimed that these eco-taxes only deter people from flying and reduce demand. IATA has indicated its opposition to them, stating, "While the overall goal of such taxation is laudable, it has proven to be an ineffective policy choice as it negatively impacts passengers, other airline customers, jobs and the economy, without incentivising newer and greener technology"(IATA, 2019b). The association has further stated that "Governments need to support multilateral efforts to address aviation's emissions, including CORSIA... (and) investment in research in new technologies and the transition of air transport towards sustainable aviation fuels"(IATA, 2019b).

Besides taxation, policies that encourage customer involvement by pricing carbon emissions into tickets, airport departure taxes, baggage, etc. can also play a certain role in helping bridge the price gap. At a 5% biojet blend, the additional cost of a transatlantic flight per passenger would be about USD 15-20.

Movements such as the Swedish "flygskam" (flight shame) have raised awareness of the overall sustainability of aviation, but these so-called eco-taxes are unlikely to directly encourage biojet fuel production and consumption.

Policies to promote a reduction in the carbon intensity of jet fuels

To date, the majority of successful biofuel policies have involved volumetric mandates, requiring a defined amount of bioethanol or biodiesel to be blended with petroleum-based fuels; the carbon and overall emission reductions resulting from using these blends is not generally considered. As many of these policies were originally based on an energy security rationale rather than climate change mitigation, these policies could be modified to incentivise emission and carbon reductions. They could, for example, discourage the use of feedstocks and processes that provide little climate benefit while encouraging the use of low-carbon-intensity or waste feedstocks, and substituting fossil-derived electricity with renewable electricity. As sustainability and overall carbon reduction are the central focus of sustainable aviation fuel and biojet development, any policies should promote the production and use of fuels with the lowest carbon intensity.

As well as promoting biojet fuels, future policies need to also promote the production of all low-carbon-intensity fuels used for transport

Most of the technologies used to make drop-in biofuels result in the production of multiple low-carbon-intensity products such as light gases, naphtha, gasoline, jet, diesel and heavy fuel oils. Although the volume of the different fuel products may vary between different technologies and refining approaches, the biojet fraction is only one of several products. While additional processing could increase the amount of biojet obtained (e.g. cracking of large molecules or alkylation of smaller molecules), this will generally increase the cost of production, with cracking generally resulting in increased amounts of lower-value products such as gases.

The approximate volume of the biojet fraction produced by the different processes is summarised in Table 7, with typical upgrading of HEFA producing mostly renewable diesel and about 15% of the original feedstock going to the biojet fraction. As the renewable diesel stream contains larger hydrocarbon chains, additional hydrocracking steps can be carried out to increase the biojet fraction to about 50%. This results in higher processing costs and a 10% loss in liquid product yield (Pearlson, 2011); it is also likely that additional processing will increase the carbon intensity of the jet fuel fraction.

TABLE 7. Approximate percentage of the biojet fraction produced by different technologies

Technology	Approximate jet fraction
HEFA upgrading	15-50%
ATJ	70%
FT synthesis	25-40%
Upgrading of biocrudes from pyrolysis, hydrothermal liquefaction, etc.	10-30%

Technology-agnostic policies to incentivise investment in lower-carbon-emission technologies

As demonstrated by the California Air Resources Board (CARB), an LCFS establishes emission reduction targets without specific reference to the volumes of biofuel that must be blended into conventional petroleum fuels.[21] For example, an LCFS policy may require a 10% reduction in emissions by 2025, placing the burden on fuel suppliers to meet this target through blending with biofuels or purchasing credits from other fuel suppliers that have achieved greater reductions than the target. Companies may also be penalised for every tonne of CO_2-eq they emit above this target. As demonstrated in jurisdictions such as California and British Columbia, the emission reduction target can be gradually increased, with the carbon intensity of a fuel assessed using LCA models such as GREET[22] and GHGenius.[23]

Policies such as the LCFS have been effectively used in the transport sectors of some regions, creating a direct link between incentives and the carbon intensity of the fuel. Consequently, this has encouraged the development of technologies that improve the carbon intensity of fuels. Unlike carbon pricing systems such as cap and trade policies, LCFS policies only apply to transport, with the revenue generated from high-carbon-intensity fuels subsidising low-carbon-intensity fuels. California approved an opt-in mechanism for aviation biofuels on a voluntary basis in 2018. Although this could result in an effective cross-subsidisation of aviation by road users, in the short term it is not likely to create a significant distortion due to the low volumes of biojet fuel that are currently available (Searle et al., 2019).

Ensuring "sustainability" is incorporated into any biojet fuel policies

Biojet fuels must be certified as sustainable according to ICAO's CORSIA standards to be eligible for the scheme. They must meet high sustainability standards along the entire supply chain, including feedstock, processing, conversion, upgrading and distribution. Examples of existing policies with built-in sustainability

21 https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard/about.

22 https://greet.es.anl.gov/.

23 www.ghgenius.ca/.

requirements are the US Renewable Fuel Standard (US EPA, n.d. a) and the EU Renewable Energy Directive (European Commission, n.d. b). The US standard categorises biofuels according to their emission reduction potential and the available incentives are categorised via the Renewable Identification Number system (US EPA, n.d. b). However, a drawback of the categorisation is that it does not encourage improvement in carbon intensity within a category.

It should be noted that the sustainability of a fuel is not limited to its emission reduction potential as broader sustainability characteristics also need to be applied. ICAO has determined minimum sustainability characteristics, which are subject to periodic review.

The role of airports in promoting and facilitating biojet fuel use

Several successful biojet fuel initiatives have been organised around an airport, bringing together multiple stakeholders. This has proven to be an effective strategy that incorporates the complex downstream supply chain with technical regulations on using biojet fuel within the airport hydrant system. The bioport concept, as described by SkyNRG, is an illustration of this type of initiative (SkyNRG, n.d.). Another example is the Seattle-Tacoma International Airport, where it is stated that, "The … airport [Sea-Tac] can leverage its unique position at the intersection of airlines, fuel suppliers, governments and communities to support the scale-up of sustainable aviation fuel. Airports can aggregate fuel demand across airlines and play an integral role in their regional economy. Bold leadership from airports will accelerate industry sustainability and sustainable aviation fuel adoption."(Benn et al., 2017). A key part of this study looked at innovative funding options including corporate support, use of airport funds to support broader environmental benefits, and also levying an additional fee on airlines (Benn et al., 2017) with a central airport fund used to establish the required infrastructure.

This type of model is currently being assessed at a number of airports in Europe, with specific actions dependent on regulations, the governing structure of the airport and local conditions. These projects have also assessed the use of airport incentives to encourage airlines to use biojet fuels, as well as applying fees on passengers and using the funds to directly support biojet use (Benn et al., 2017).

As discussed below, airports are uniquely positioned to bring together multiple stakeholders and can play an important role in supply chains.

11. DEVELOPING SUPPLY CHAINS FOR BIOJET FUELS

Although oleochemical/lipid feedstocks are currently the primary feedstocks used to make biojet fuels, in the longer term thermochemical technologies will use feedstocks such as biomass and residues to make low-carbon-intensity fuels. While some parts of the process pathway have established regional/local supply chains (e.g. wood pellets and waste lipids), future biojet fuel pathways are likely to be based on current infrastructure (such as repurposed oil refineries), available feedstocks, and regional conditions and policies.

Establishing a robust supply chain requires the inclusion of key considerations:

- Feedstock availability and cost; maturity of the supply chains; competing uses; overall sustainability and current certification. A recent report from World Economic Forum proposes a set of criteria for determining sustainability (McKinsey & Company, 2020a).
- Suitability of the technology for the region (based on feedstocks and existing infrastructure). For example, some current HEFA facilities are repurposed oil refineries that have been converted to drop-in biofuel facilities. Depending on the available regional refinery infrastructure, co-processing within existing refineries could be possible.
- Existing refinery infrastructure and supply chains for fuel distribution.
- Existing airports and mechanisms already in place to ensure sustainability.
- Total transport fuel demand and jet fuel demand (international jet fuel demand).
- Policies that promote drop-in biofuel production and biojet specifically.
- Financing sources available to build/repurpose infrastructure.
- Identifying stakeholders (including government) and developing a roadmap with targets and clear objectives for implementing biojet fuel production.

For example, ICAO has funded various feasibility studies for a number of countries (e.g. Burkina Faso), assessing what components might be already in place and what will be needed (Weber, 2017).

However, establishing biojet production in developing countries is likely to generate local challenges, such as food security being a far bigger concern and the need to clearly document the integration of biofuel and food production. Sustainable food and fuel production will have to be ensured.

In most developing countries, a far greater proportion of lipids and biomass are used as food or for traditional heating and cooking applications. Thus, any feedstocks that might be used to make biojet fuel must also consider all other possible uses for this resource.

It should be noted that countries such as Indonesia, Malaysia and Argentina are major producers and exporters of vegetable oils (OECD-FAO, 2020). The production of these crops contributes significantly to rural jobs and the local economy. However, there are concerns about the overall sustainability of potential biojet fuel from feedstocks such as palm oil. As the major cost in the overall HEFA-based biojet process is the feedstock – and palm has been shown to be among the most productive lipid sources per hectare – renewed efforts should be made to certify palm plantations that can show that they operate sustainably.[24] Sustainability in this case is complex, as broader concerns around land use change and indirect land use change need to be considered.

Provided the sustainability issues can be addressed, these developing regions are well positioned to become the primary oleochemical/lipid suppliers, both locally and internationally. Companies such as Neste (e.g. at its Singapore facility) recognise the potential of these regions to both increase the amounts and reduce the cost of these biojet fuel feedstocks. Sustainability has to be verified according to standards as set out by the certification body (e.g. RSB). In the case of biojet, the absence of sustainability certification will make the biofuel ineligible under CORSIA to meet an airline's offset obligations. Most major airlines would be likely to refuse to purchase uncertified biojet in any case, as the sector has made a strong commitment to sustainability.

24 E.g. certified under the Roundtable for Sustainable Palm Oil (RSPO) (https://rspo.org/about).

12. CONCLUSIONS

The deep decarbonisation of the aviation sector by 2050 will require concerted action on multiple fronts and the use of a range of different solutions, including new propulsion systems such as electric and hybrid aircraft and the use of hydrogen. However, to achieve early reductions in emissions in the 2020s and 2030s, and deep reductions by 2050, the use of sustainable aviation fuels will be essential. Biojet is currently the most certified type of sustainable aviation fuel and whilst over time synthetic fuels will become available, biojet holds the most promise for cost-effective scale-up and use in the 2020s and 2030s, and is likely still to be playing a major role in the 2040s.

However, to date very little biojet fuel has been used, with limited availability, high costs and a lack of policy drivers impeding its development. Significant progress has been made recently in several areas, such as ASTM certifying new biojet production routes, various airports successfully using airport fuel hydrant systems to deliver biojet/jet fuel blends and over 315 000 flights using some percentage of biojet fuels. But the production and use of these lower-carbon-intensive fuels remains small, contributing less than 1% of all of the jet fuel that is currently used.

It is, in principle, possible to rapidly increase the amount of biojet fuels available. However, past experience has shown that challenges in the various process steps, such as establishing supply chains, construction and commissioning, often result in lengthy delays before full production capacity can be reached. The starting point should be to “tweak” existing renewable diesel facilities to potentially add more than 1 billion litres per year of additional biojet fuel, which will require only limited capital investment. In addition, several other standalone refineries are being repurposed to operate using 100% renewable feedstocks (e.g. Phillips 66). In parallel, a co-processing approach to lowering the carbon intensity of all of a refinery’s fuels, and the ongoing construction of several biorefineries using advanced technologies (e.g. gasification/FT, ATJ), will all contribute to increasing the availability of biojet.

The future production and use of biojet fuels will be primarily influenced by the three challenges of feedstock, technology and policy. For the immediate future, biojet fuel will be produced via the HEFA-based oleochemical/lipid-based process, which is relatively simple and already at a fully commercial scale. However, oleochemical/lipid feedstocks are typically expensive (more expensive than conventional jet fuel itself), with their overall sustainability and carbon intensity of ongoing concern. As a result, there is increased focus on sourcing greater volumes of low-cost, low-carbon-intensive feedstocks such as FOGs. However, these types of feedstock are only available in limited amounts, with a consequential impact on their price. The overall sustainability of the oils derived from vegetable crops such as rape, sunflower and soya is under increasing investigation, while their cost continues to be a major impediment.

An alternative to repurposing refineries as standalone facilities producing lower-carbon-intensive drop-in biofuels is to co-process the lipid feedstocks at an appropriate insertion point (e.g. hydrotreater) in existing petroleum refineries. This reduces the overall carbon intensity of the fuels that are produced. Co-processing lower-carbon feedstocks such as lipids/biocrudes in a refinery's hydrotreater is likely to be a relatively easy way of making lower-carbon-intensive jet fuels and, with limited investment costs, could significantly expand the volumes of low-carbon-intensity jet fuels available. It is worth noting that good progress is being made in tracking "the green molecules" and documenting how the carbon intensity of the final fuels has been reduced.

In the medium to longer term, the oleochemical/lipid co-processing route will be supplemented by biocrudes/bio-oils produced via thermochemical processes that use biomass as the feedstock, in the hope that they will be more plentiful, cheaper and more sustainable than lipids. Some of these technologies are nearing commercialisation, such as gasification and FT synthesis, and the ATJ process. However, it is likely that it will still take some years for these so-called advanced technologies to reach full commercialisation, with each needing to resolve ongoing technical and economic issues. For example, studies to date have indicated that gasification-based biojet fuel involves high capital costs, while technology challenges such as syngas clean-up still have to be fully resolved. Although ATJ processes have been ASTM approved and the resulting biojet successfully used in some flights, the relatively high value of the alcohol intermediates and current policy drivers encouraging their use in road transport are ongoing challenges. Efforts to reduce the carbon intensity of the alcohol produced from sugar (cane) and starch (corn/wheat) will also help reduce the carbon intensity of any jet fuels produced from these feedstocks. They include replacing coal-derived electricity with wind/solar-derived electricity.

Biojet production via the upgrading of pyrolysis- or hydrothermal liquefaction-derived biocrudes is still in development, but recent techno-economic analyses have suggested that these processes could, eventually, produce cheaper biojet fuels. Unfortunately there do not appear to be any companies currently targeting these technologies specifically, and no ASTM certification for this production route is in the pipeline.

For the foreseeable future, lower-carbon-intensive jet fuels are likely to be considerably more expensive than conventional jet fuels. Consequently, in the same way that policies have and continue to play a key role in encouraging the production and use of bioethanol, biodiesel and renewable diesel, biojet fuel development will need effective policies to overcome the significant price differential between biojet and fossil-derived jet fuels.

Effective policy support will be essential in the short to medium term to bridge this price gap. As established technology push and market pull biofuel policies have been shown to act in complementary ways, promoting development and market penetration, an effective combination of biojet fuel policies will be important. The production of conventional biofuels (e.g. bioethanol/biodiesel) involves relatively mature technologies that have been primarily promoted by market pull policies such as mandates/quotas. However, a similar policy approach is unlikely to be as effective for biojet fuels as many of the technologies are not yet mature, with initial capital investment proving to be a major barrier. Thus, a greater focus on technology push policies, including capital investment financing, will be important. As most airlines are eager to purchase biojet fuels and several off-take agreements have already been signed to access future volumes, biojet fuel mandates are likely to play a bigger role in future market pull policies.

Although CORSIA has placed a price on carbon, which will require airlines to purchase offsets to maintain carbon-neutral growth after 2020, these emission reductions are likely to occur outside rather than inside the aviation sector. Therefore, offsets are unlikely to stimulate the production of biojet fuels, even though eligible fuels can be used to meet offset objectives. Significant carbon emission reductions inside the aviation sector will be needed to achieve the deep decarbonisation of the global energy system.

Thus, it is likely that effective domestic policies will be needed if we are to boost biojet fuel production and use. Various mechanisms can be used to incentivise biojet fuel production, including opting biojet into existing policies and using a fuel multiplier to address competition with other fuels. Any biojet fuel policies should also be in the form of low-carbon fuel-type standards rather than volumetric mandates, as sustainability and emission reduction aspects need to conform with ICAO's standards. It is worth noting that biojet fuels are (almost) always produced as one of a mixture of low-carbon fuel products. Thus, rather than just targeting lower-carbon-intensive jet fuels, decarbonising all of the fuels produced by a refinery should be encouraged as jet fuel production is, typically, integrally linked to the production of all liquid transport fuels (e.g. for cars, trucks, marine and rail).

The current global disruption brought by the COVID pandemic has confirmed how much the world is inexorably linked, with sectors such as aviation disproportionately disrupted. However, the slower but much higher-impact results of climate change will undoubtedly have an even greater disruptive influence, with all aspects of the world's environment, social structure and economy affected. There are several ways to decarbonise many aspects of the global economy, such as via increased efficiency and the use of renewable energy sources such as hydro, wind and solar. But the long-distance transport sector, and aviation in particular, will be highly dependent on sustainably produced, low-carbon-intensive jet fuels. If the aviation sector is to meet its ambitious carbon reduction targets, the production and use of lower-carbon-intensive jet fuels, including biojet, need to be encouraged, with the right policies put in place to help the sector meet its sustainability aspirations.

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ANNEX A

DETAILED BREAKDOWN OF REFERENCES FOR UCO COLLECTION

Region	Collected UCO estimate (Mt/year)	Collection ratio range (%)	Total potential for UCO (Mt/year)	Sector	Source
Asia = 10.549 Mt					
China	0.313	5.6	5.582	Hotels, restaurants and caterers	(Tsai, 2019; Teixeira et al., 2018)
India	0.002	0.1	2.000	Households and restaurants	(Pavlenko and Searle, 2019; Teixeira et al., 2018)
Indonesia	0.828	50.0	1.656	Hotels, restaurants and caterers	(Kharina et al., 2018)
Japan	0.288	71.9	0.401	Households and restaurants	(Teixeira et al., 2018)
Malaysia	0.275	55.0	0.500	Hotels, restaurants, caterers and small eateries	(Kabir, Yacob and Radam, 2014; Pelemo et al., 2020)
Republic of Korea	0.235 0.075 0.014	98.0 78.6 18.6	0.240 0.095 0.075	Institutional food centres Restaurants Households	(Cho et al., 2015)
Oceania = 0.056 Mt					
Australia	0.028	55.2	0.051	Households and restaurants	(Wang, 2013)
New Zealand	N/A	N/A	0.005	Restaurants	(Bioenergy Association of New Zealand, 2015)
Middle-East = 0.259-0.306 Mt					
Saudi Arabia	0.00073	13.7	0.00532	Collected mainly at Makkah's restaurants and pilgrimage centres	(Shahzad et al., 2017)
Turkey	0.038-0.060	15-20	0.253-0.300	Hotels, restaurants and caterers	(Arslan and Ulusoy, 2018)
United Arab Emirates	0.00017	62.4	0.00027	Only some eateries from Dubai	(Baldwin, 2017)

Africa = 1.154-1.270 Mt					
Egypt	0.050	10.0	0.500	Hotels, restaurants and caterers, food factories	(South-South World, 2017)
Ghana	0.034	20-63	0.054-0.170	Hotels from 5 major cities (Accra, Kumasi, Sunyani, Takoradi, Tamale)	(Mensah and Obeng, 2013)
South Africa	0.143	23.8	0.600	Frying facilities, fast food	(Pelemo et al., 2020)
South-America = 3.107 Mt					
Brazil	0.049	1.7	2.882	Households and restaurants	(César et al., 2017)
Colombia	0.050	22.2	0.225	Industrial frying and domestic use	(Rincón et al., 2019)
North-America = 3.910 Mt					
Canada	0.081	55.0	0.147	Hotels, restaurants, caterers, food factories and households	(Chhetri et al., 2008; Teixeira et al., 2018)
Mexico	0.375	44.6	0.840	Hotels, restaurants, caterers, food factories and some households	(Sheinbaum-Pardo et al., 2013; Viornery-Portillo et al., 2020)
United States of America	1.140	39.0	2.923	Hotels, restaurants and caterers	(Teixeira et al., 2018)
Europe = 3.550 Mt					
Belgium	0.030	46.8	0.064	Households mainly	(Teixeira et al., 2018)
Croatia	0.019	74.0	0.026	Households and restaurants	(Greenea, 2017; Teixeira et al., 2018)
Cyprus	0.001	25	0.004	Restaurants, households, catering	(Greenea, 2017; Teixeira et al., 2018)
Czech Republic	0.011	26.2	0.042	Households and commercial	(Greenea, 2017; Teixeira et al., 2018)
Denmark	0.020	71.4	0.028	Eateries and village households	(Teixeira et al., 2018)
Finland	0.004	25.0	0.016	Households	(Teixeira et al., 2018)
France	0.044	50.3	0.087	Households	(Greenea, 2017; Teixeira et al., 2018)
Germany	0.493	100.0	0.493	All sectors	(Teixeira et al., 2018)
Greece	0.051	74 .0	0.069	Households	(Teixeira et al., 2018)
Hungary	0.004	8.8	0.045	Households and restaurants	(Greenea, 2017; Teixeira et al., 2018)

Ireland	0.022	67.8	0.032	Catering, food factories and households	(Teixeira et al., 2018)
Italy	0.212	78.7	0.269	Households and restaurants	(Teixeira et al., 2018)
Netherlands	0.044	76.5	0.058	Households and commercial	(Teixeira et al., 2018)
Portugal	0.032	58.7	0.055	Households and restaurants	(Teixeira et al., 2018)
Spain	0.110	36.8	0.299	Households and restaurants	(Teixeira et al., 2018)
United Kingdom of Great Britain and Northern Ireland	0.091	27.7	0.329	Restaurants	(Teixeira et al., 2018)
			1.916		
Europe (if the total potential of all member states is considered)	N/A		**3.550**	All sectors	(Toop et al., 2014)

ANNEX B

PRODUCTION COST AND MINIMUM FUEL SELLING PRICE (MFSP) OF BIOJET FUEL (USD/L)

Technology	Feedstock type	CAPEX	OPEX	Feedstock	Production cost	MFSP	Source
HEFA/HVO	UCO	0.10	0.26	0.86	1.22	1.22	(de Jong et al., 2015)
	Yellow grease	0.20	0.19	0.58	0.97	0.66-1.24	(Bann et al., 2017)
	Tallow	0.20	0.19	0.73	1.12	0.79-1.42	(Bann et al., 2017)
	Soybean oil	0.20	0.19	0.85	1.24	0.87-1.6	(Bann et al., 2017)
	Jatropha oil	0.09	0.14	2.07	2.29	1.81	(Neuling and Kaltschmitt, 2018)
	Palm oil	0.08	0.13	1.04	1.25	0.80	(Neuling and Kaltschmitt, 2018)
	Vegetable oil	0.33	0.17	1.59	2.09	1.78	(Diederichs et al., 2016)
	UCO	0.10	0.13	0.55	0.78	0.56-1.0	(Brown et al., 2020)
Gasification/FT	Forest residues/ wheat straw	0.63	0.62	0.87	2.12	1.63-2.40	(de Jong et al., 2015)
	Biomass	0.64	0.24	0.37	1.26	0.82-1.58	(Brown et al., 2020)
	All wastes	0.67	0.33	0.00	1.00	0.58-1.14	(Brown et al., 2020)
	MSW	0.93	0.34	0.00	1.27	0.95-1.39	(Bann et al., 2017)
	Lignocellulose	1.03	0.50	0.75	2.29	1.95	(Diederichs et al., 2016)
Pyrolysis, bio-oil and upgrading	Forest residues/ wheat straw	0.28	0.54	0.53	1.34	1.18-1.67	(de Jong et al., 2015)
	Forest residues/ wheat straw (bio-oil co-processing)	0.58	0.05	0.56	1.20	0.87-1.53	(Brown et al., 2020)
	Forest residues/ wheat straw (bio-oil stand-alone)	0.42	0.48	0.25	1.15	0.90-1.4	(Brown et al., 2020)
	Forest residues/ wheat straw (FP bio-oil)	0.35	0.28	0.24	0.87	0.90	(Jones et al. 2013)
	Woody biomass (FPH)	1.21	0.95	0.15	2.31	1.02-2.1	(Bann et al., 2017)

ATJ	Forest residues/ wheat straw (mixed alcohols)	0.58	0.96	1.11	2.65	2.17-3.16	(de Jong et al., 2015)
	Ethanol	0.10	0.23	1.23	1.56	0.75	(Geleynse et al. 2018)
	Isobutanol	0.05	0.16	1.38	1.59	0.59-0.89	(Geleynse et al. 2018)
	Wheat straw/ isobutanol	0.24	0.38	1.03	1.65	1.20	(Neuling and Kaltschmitt, 2018)
	Wheat grain/ isobutanol	0.09	0.32	0.85	1.25	0.75	(Neuling and Kaltschmitt 2018)
	Corn grain/ ethanol-nth plant	0.47	0.31	0.82	1.60	1.11	(Tao et al. 2017)
	Corn stover/ ethanol-nth plant	0.73	0.50	0.55	1.79	1.62	(Tao et al. 2017)
	Sugarcane	N/A	N/A	N/A	0.93	0.96	(Yao et al. 2017)
	Corn grain	N/A	N/A	N/A	0.97	1.01	(Yao et al. 2017)
	Switch grass	N/A	N/A	N/A	1.34	1.38	(Yao et al. 2017)
	sugarcane fermentation	0.75	0.83	0.94	2.52	2.03	(Diederichs et al. 2016)
Advanced Fermentation	Sugarcane (advanced)	0.64	0.17	0.69	1.50	1.10-1.96	(Bann et al., 2017)
	Corn grain (advanced)	0.56	0.26	1.02	1.84	1.30-2.1	(Bann et al., 2017)
	Herbaceous biomass (advanced)	1.26	0.71	0.46	2.43	2.16-2.92	(Bann et al., 2017)
	Lignocellulose (syngas)	0.76	0.53	0.75	2.05	1.99	(Diederichs et al. 2016)
Catalytic Hydrothermolysis	Brown grease	0.51	0.24	0.47	1.21	0.41-0.82	(Mcgarvey, Tyner, and Lafayette 2018)
	Yellow grease	0.72	0.11	0.69	1.52	0.61-1.11	(Mcgarvey, Tyner, and Lafayette 2018)
	Carinata oil	1.08	0.40	1.10	2.59	1.18	(Mcgarvey, Tyner, and Lafayette 2018)

Biogas to liquids (Bio-GtL)	German substrate mix	0.28	0.15	2.85	3.28	2.58	(Neuling and Kaltschmitt, 2018)
	Manure	0.28	0.15	2.24	2.67	1.97	(Neuling and Kaltschmitt, 2018)
	Wheat straw	0.42	0.43	1.14	2.00	1.52	(Neuling and Kaltschmitt, 2018)
	Willow	0.40	0.48	0.51	1.38	0.95	(Neuling and Kaltschmitt, 2018)
Hydrothermal Liquefaction (HTL)	Forest residues/ wheat straw	0.23	0.38	0.39	1.00	0.81-1.18	(de Jong et al., 2015)
	Woody biomass	2.41	1.06	0.70	4.17	2.09-3.58	(Bann et al., 2017)
SIP	Forest residues/ wheat straw	0.91	2.34	1.82	5.07	4.34-5.79	(de Jong et al., 2015)
Aqueous phase reforming (APR)	Woody biomass	1.38	0.78	0.38	2.54	1.73	(Bann et al., 2017)
PtX and FT	CO_2 from direct air capture	N/A	N/A	N/A	N/A	3.81	(Schmidt et al., 2018)
	CO_2 from a concentrated source	N/A	N/A	N/A	N/A	3.46	(Schmidt et al., 2018)

Notes: FPH = fast pyrolysis and hydroprocessing; PtX = Power-to-X; SIP = synthesised iso-paraffins. Exchange rate used for conversions EUR 1 = USD 1.18. Density of jet fuel = 0.8 kg/L. Calorific value of jet fuel = 43.8 MJ/kg (or) 43.8 GJ/tonne. Conventional jet fuel price as on 13 November 2020 = USD 0.264/litre = USD 361/Mt (www.iata.org/en/publications/economics/fuel-monitor/). This price was 41.5% lower than in November 2019. Breakdown of cost elements was calculated based on the corresponding studies and the numbers could be different from the original studies.

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