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ABOUT IRENA

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Insights for Policy Makers

- If the aviation sector were a country, it would be the eighth-largest emitter of greenhouse gases (GHG) in the world, at 2% of the human-induced total. In 2010, carbon dioxide (CO_2) emissions from international aviation amounted to 448 megatonnes (Mt), with forecasts of increased emissions ranging from 682 Mt to 755 Mt by 2020, and as high as 2 700 Mt by 2050 if no action is taken (ICAO, 2016).[1] Airlines carried nearly 3.6 billion (bln) passengers in 2015.

- Given this sector's growing contribution to global CO_2 emissions, aviation will play a key role in meeting the international climate targets set forth in the 2015 Paris Agreement, even though the document does not specifically mention aviation emissions.

- Many airlines, aircraft manufacturers and industry associations have committed to voluntary, aspirational targets that would collectively achieve carbon-neutral growth by 2020 and a 50% reduction in GHG emissions by 2050 (relative to 2005 levels).

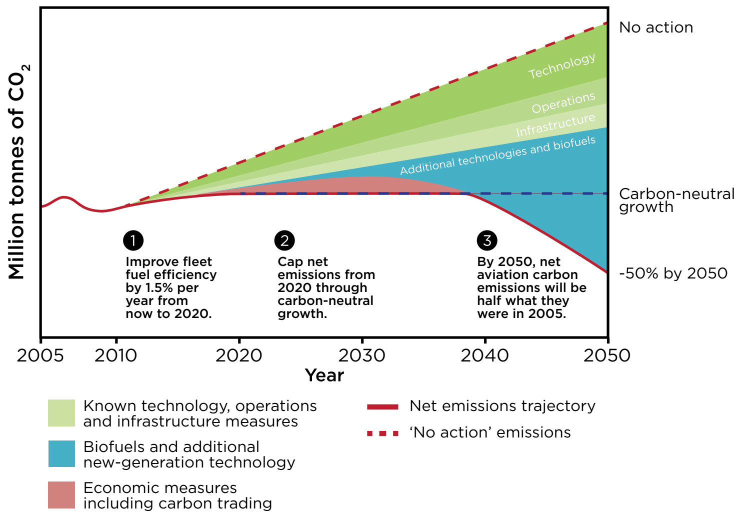
- Emissions can be reduced by 1.5% annually through improved fuel efficiency in new aircraft, aircraft modifications, airport restructuring, and optimised navigational systems. However, a significant longer-term reduction of emissions would require airlines to use more fuels that are renewable and sustainable, such as biofuels developed for jet aircraft (Figure 1).

- Although sustainable and clean alternative propulsion technologies are in development, such as electric- or solar-powered aircraft and the use of cryogenic hydrogen, these options are unlikely to be ready for commercial use until well after 2050. Given that aircraft have a long life span and are very expensive, airlines typically want to use them as long as possible before replacing them.

- Biofuels for jet aircraft are known in the industry as "biojet" or "bio-jet" fuels. They are the only real option to achieve significant reductions in aviation emissions by 2050. Bio-jet fuels can be derived from sustainable sources such as vegetable oils and animal fats, and existing jet engines do not require modifications for their use.

1 Based on a calculation of 316 kilograms (kg) of CO_2 emitted per kg of fuel, and forecasts for fuel consumption increases. See Figure 5 on page 19 of the report. Note that the figure excludes fuel consumption for domestic aviation.

Figure 1: Emissions from aviation in the absence of any action, and emissions-reduction goals set by the industry



Source: Air Transport Action Group

Bio-jet fuels can potentially reduce GHG emissions compared to fossil-based jet fuel, according to a well-to-wheel life-cycle analysis. However, the emissions-reduction potential of different feedstocks may differ significantly, with values ranging from 50% to 95% of the claimed potential reduction when compared with fossil jet fuel[2] (EU Directives, 2015).

Achieving the GHG emissions-reduction targets proposed by the aviation industry (Figure 1) and by organisations such as the International Civil Aviation Organisation (ICAO) will require a significant increase in bio-jet fuel production and consumption. The exact volumes required to achieve specific goals are not clear because of factors such as the aviation sector's future fuel consumption, the extent of emissions reductions achieved through offsets,[3] and the specific emissions-reduction potential of various options for making bio-jet fuels, which are called pathways.

2 The EU Renewable Energy Directive, Annex V, Section B contains default values for GHG savings through biofuels, which can be used as a guideline. Diesel using a wood-based Fischer-Tropsch process has a default value of 95%, for example, while typical GHG savings values for hydrotreated vegetable oil range from 40% to 65% based on different feedstocks.

3 A carbon offset is a reduction in emissions of CO_2 or GHG made in order to compensate for or to offset an emission made elsewhere.

Fuel consumption for international aviation could be as high as 852 million tonnes (Mt) by 2050 (ICAO, 2016), and could require 426 Mt of bio-jet to meet the GHG emissions-reduction goals. Current production, however, is currently very limited, at less than 0.1% of global total consumption of all types of jet fuels. This technology brief will explain how supply at that level will require significant policy, technological, and supply-chain support for bio-jet fuel development. The effort would be similar to what was required in the U.S. and Brazil to establish conventional biofuels such as bioethanol and biodiesel for road transportation.

The vast majority of bio-jet available now is derived from oleochemical[4] feedstocks such as vegetable oil, animal fats, and used cooking oil (UCO). However, costs for these feedstocks, as well as supply and sustainability concerns, make it impossible to scale up production to meet demand.

The oleochemicals-to-bio-jet fuel pathway will not supply all future needs, but is the foundation technology used to establish initial supply chains. Advanced technologies have the potential to meet long-term goals, but are at leave five to 10 years away from commercial maturity. These technologies use other feedstocks, such as forest or agricultural matter or other lignocellulosic biomass, waste streams,[5] and algae. The most likely conversion technology for these advanced-bio-jet pathways will likely be thermochemical, instead of biochemical. This is because intermediate products derived from biochemical routes will likely fetch a higher price from buyers outside the aviation sector.

"Conventional bio-jet" will establish initial supply chains, while "advanced bio-jet" technologies, based on lignocellulosic biomass or algal feedstocks, are developed

4 An oleochemical is a chemical compound derived industrially from animal or vegetable oils or fats.

5 Waste streams include can be either municipal solid waste or industrial waste. The latter category includes waste gases from the steel, chemical or cement industries.

As of May 2016, the American Society for Testing and Materials (ASTM) had certified four different technology pathways to produce bio-jet fuels. ASTM certification is required before commercial airlines can use a fuel for an international flight. The four pathways are:

- Hydroprocessed Esters and Fatty Acids (HEFA bio-jet), using oleochemical feedstocks such as oil and fats. This is the foundation technology, which ASTM certified in 2011.
- Gasification through the Fischer-Tropsch method (FT), using municipal solid waste (MSW) or woody biomass as feedstock. ASTM certified it in 2009.
- Synthesised Iso-Paraffinic fuels (SIP), formerly known as the direct sugars-to-hydrocarbon route (farnesane). Certification came in 2014.
- Alcohol-to-jet based on isobutanol (ATJ), certified in 2016.

Today, the vast majority of currently available commercial volumes of bio-jet fuels are HEFA bio-jet, and a number of commercial-scale facilities can produce it.[6] However, the same process also creates renewable diesel (HEFA-diesel), for which there is a larger market and higher sales prices. Producers are therefore focused on this product instead of on HEFA-jet. HEFA-diesel is also known as green diesel or hydrotreated renewable diesel. Two production facilities based on the FT pathway were expected to begin production in late 2016 in the U.S. In total, the operational capacity of the world's current HEFA facilities is about 4.3 bln Liters per year. Even if all of this were to be used to make bio-jet, supply would still amount to less than 1.5% of the world's jet fuel requirements.

Although bio-jet biomass through gasification and subsequent FT conversion is not yet a commercial activity, two facilities are planned. The companies building them are Fulcrum Bioenergy, with a planned production of 37 m L/y of biofuel from MSW; and Red Rock Biofuels, with a planned production of 45 m 1 bln L/y. using wood as the feedstock. Kaidi has proposed a third facility in Finland, with a capacity of 1 L/y. These volumes describe the anticipated total fuel production of each plant, of which bio-jet would be only one type.

The development and deployment of bio-jet fuels, primarily HEFA bio-jet, has progressed from single demonstration flights by airlines or equipment manufacturers to multi-stakeholder supply-chain initiatives including equipment manufacturers, airlines, fuel producers and airports.

6 Note that most of these facilities would have to modify their production process in order to produce jet fuel.

Although several airlines have invested in bio-jet production and research, most are simply customers that have signed short-term off-take agreements to use bio-jet in trial runs. There are now about 100 bio-jet initiatives, and in the period from 2009 to 2015 the pace of new ventures has increased from less than five a year to a range of 10 to 20. Examples include, in the Middle East, the Abu Dhabi-based airline Etihad's supporting for research on halophytic (saltwater-tolerant) plants as feedstock for bio-jet fuels. Leadership from individual countries could come from the U.S. and Brazil, thanks to their experiences establishing ethanol markets and because of the availability of sugar- and starch-based feedstocks in those countries. Large palm-oil producing countries, such as Indonesia and Malaysia, could also explore the use of this crop for bio-jet.

One of the main reasons such small amounts of bio-jet are currently used is the high cost of production. This is a major challenge because fuel accounts for about 30% of the total expense of operating an airline.[7] HEFA-bio-jet has historically cost more than fossil-derived jet fuels, and potential feedstocks for HEFA-bio-jet alone often cost more than traditional jet fuel, with the cost of converting them into HEFA-bio-jet adding to the price gap from there. In January 2016, for example, the cost of palm oil[8] was USD 0.45/L, while the price of jet fuel was USD 0.25/L. Pricing for advanced bio-jet fuels based on lignocellulosic feedstocks is less clear as these technologies are still in the demonstration phase and not yet commercially available. However, they are also expected to cost more than fossil fuels. Another challenge for the aviation sector will be competition with ground-based transportation biofuels such as biodiesel, for which some governments have already established policies to encourage feedstock production and biodiesel use. Currently, there are no policies that would encourage the preferential diversion of oleochemical-derived feedstocks (vegetable or animal) from road-transport fuels to aviation.

Specific policies to promote bio-jet will be crucial if the global aviation sector is to reach its 2020 and 2050 targets for GHG emissions reductions. The international nature of air travel will further complicate policy development. At the international level, the ICAO has reached an agreement on a global market-based measure (GMBM) scheme to reduce aviation-derived carbon emissions through offsetting[9] (see footnote 3). However, implementation will not begin until 2021, and emissions from some countries, particularly developing ones, are unlikely to be

7 www.atag.org/facts-and-figures.html

8 Used here as a reference point as it is the lowest priced vegetable oil.

9 www.icao.int/Newsroom/Pages/Historic-agreement-reached-to-mitigate-international-aviation-emissions.aspx

regulated. Although carbon offsets will contribute to global emissions reductions, it is unclear whether they will drive bio-jet development. Comprehensive policies are highly likely to be needed at both the national and international levels to incentivise bio-jet production and consumption. Currently, the Netherlands, Norway and the U.S. have established policies to encourage bio-jet fuel production, and some others have announced aspirational targets. Others, including Indonesia, have proposed a bio-jet mandate. However, there are currently no bio-jet-specific policies to encourage commercialisation of the entire supply chain, as there were for bioethanol and biodiesel when those fuels were at the development stage bio-jet is at now. This is mainly due to the international nature of aviation. There is a greater degree of local control over road transportation, making policy reforms and targets easier to conceive and implement.

Highlights

Current technological developments in conventional and advanced bio-jet fuels

The aviation sector uses specific fuels to power aircraft, and these are usually classified as Jet A1 fuels in most regions. All jet fuel has to meet strict specifications, with ASTM providing the most common standards worldwide, including for renewable and sustainable fuels. However, as has been demonstrated during several ASTM certification processes, certification of a bio-jet conversion-technology pathway through ASTM can take years and includes rigorous fuel testing and evaluation. The four different advanced technology pathways certified under the ASTM standard D7566 as of June 2016 are briefly assessed below.

The FT method uses high-temperature treatment of any type of biomass (such as wood waste, agricultural residues or municipal solid waste, known as MSW) to produce a synthesis gas, which is then used to generate synthetic hydrocarbon fuels over catalysts. Although this was the first bio-jet pathway to obtain certification, coal was gasified for jet fuel first.

What is termed conventional bio-jet in this briefing note includes aviation biofuels derived from the hydroprocessing of oils and fats (oleochemicals) to make HEFA. This pathway accounts for the vast majority of existing bio-jet. Although a number of HEFA facilities are currently operating at a commercial scale, they predominantly produce HEFA diesel, not bio-jet. Only AltAir Fuels has dedicated bio-jet production capability, partly because of the policy drivers in the U.S. and the state of California, and because of the company's off-take agreements with airlines. Other major HEFA producers include Neste (with manufacturing locations in Rotterdam, Singapore, and Finland), Diamond Green Diesel (Louisiana), REG (Geismar, Louisiana), and ENI (Italy). Any HEFA facility that produces bio-jet also produces HEFA diesel.

The other two advanced bio-jet pathways now certified are SIP and ATJ. SIP bio-jet is produced biologically through the fermentation of sugars by microorganisms to create a hydrocarbon molecule called farnesene. This is treated with hydrogen to make another molecule called farnesane, which can be blended with petroleum-derived jet to produce a bio-jet fuel blend. The ATJ route also involves the fermentation of sugars to alcohols, such as ethanol or butanol. These are subsequently upgraded to bio-jet, as demonstrated by companies such as Swedish Biofuels and Gevo.

Although the FT pathway was the first to be certified, commercial volumes of bio-jet from biomass are small because of several challenges. They include syngas clean-up, catalyst contamination and economies of scale. Usage of SIP and ATJ bio-jet are limited because these routes are expensive and because the intermediates, such as butanol and farnesene, are worth more as chemical feedstocks or for applications in the cosmetics and pharmaceutical industries. The ATJ route from isobutanol only received certification in 2016, so uptake of this bio-jet may increase. Certification of another pathway based on ethanol could further increase uptake.

ASTM certification is a measure of a pathway's progress, as is its fuel readiness level (FRL), an indicator created by the Commercial Aviation Alternative Fuels Initiative.[10] These are important considerations for the eventual commercialisation and supply of bio-jet, but they do not reflect the production status or likely economics of a particular pathway. As well as the pathways described earlier, there are several other ways of producing bio-jet, some which are in the process of achieving ASTM certification and should be included in any assessment. For example, a fuel which blends fossil jet with low percentages of green diesel (hydrogenation derived renewable diesel, or HDRD) is currently in the certification process.

10 www.caafi.org/information/fuelreadinesstools.html, FRL is a scale reflecting fuel development

Global and Regional Market Prospects

According to the U.S. Energy Information Administration, the world's aviation sector used 310 bln L of jet fuel in 2012, accounting for 12% of global consumption of transport fuels.[11] The aviation sector is expected to grow by about 3% per year, but growth in the use of jet fuel will likely be slightly lower because of increases in fuel efficiency. Growth is expected to be driven by Asian, African and, to a lesser extent, Latin American markets, as economies in these regions expand (Millbrandt, 2013). ICAO expects jet fuel consumption for international travel to increase by 2050 to between 710 bln L and 1065 bln L (ICAO, 2016).[12]

At this time, targets for bio-jet production are mostly aspirational. The U.S. Federal Aviation Administration (FAA) suggested that 1 bln gallons (3.8 bln L) of bio-jet could be produced by 2018, and the U.S. Air Force hopes to replace 50% of conventional fuels (another 3.8 bln L) with renewable alternatives. Similarly, the European Union (EU) has suggested a target of 2 Mt of bio-jet fuel could be produced and used in the Eurozone by 2020 (2.5 bln L).

Recent reports have indicated that the EU is unlikely to reach this target.[13] Indonesia announced plans to mandate a 2% market share for bio-jet by 2018,[14] and other countries that have proposed bio-jet initiatives include Australia, Brazil, China, and South Africa. Although there is significant market pull for bio-jet development, such as animal fats, UCO and tall oil. Biomass-derived bio-jet expansion will initially be restricted by slow technology development and high investment and production costs.

11 This includes jet fuel for international and domestic aviation.

12 568 Mt to 852 Mt, with a conversion factor of 0.8 kg/L, meaning each tonne of jet fuel is 1250 L. These values may vary depending on the specific density and are used only as a reference.

13 http://ec.europa.eu/transport/modes/air/aviation-strategy/documents/european-aviation-environmental-report-2016-72dpi.pdf

14 This was amended from the initial proposal of 2016. www.icef-forum.org/annual_2015/speakers/october8/cs3/alb/pdf/20100_yusfandri_gona.pdf

Performance and Cost

Bio-jet offerings must be drop-in fuels; functionally equivalent to jet fuel (IEA Bioenergy, 2014) and performance must be equal to or better than fossil-derived jet fuels. Current ASTM-certified bio-jet can be used in blends of up to 50% with fossil derived jet fuel, depending on the type. SIP cannot account for more than 10% of the overall mix, and ATJ 30%. The absence of aromatics in this type of bio-jet restricts higher proportions. A blend with fossil jet fuel allows sufficient quantities of aromatics to ensure the integrity of engine seals of the aircraft. Notably, in several cases, bio-jet may have improved properties, such as reduced sulphur oxide (SO_2) and other emissions (ICAO, 2016).

Currently, the cost of producing bio-jet is not competitive with fossil-derived jet fuel costs; the price of jet A1, for example, was USD 0.36/L at the end of May 2016 (IndexMundi, 2016).

Even when oil prices were considerably higher than their current level of about USD 50 per barrel (USD 0.36/L),[15] bio-jet is significantly more expensive: generally in a range from two to seven times more than fossil derived jet fuel (IATA, 2015).

In September 2013, an EU report, entitled "2 million tonnes per year: A performing biofuels supply chain for EU aviation", estimated that a premium of EUR 1 500/t over and above the price of jet fuel would be required to make bio-jet competitive (Maniatis *et al*., 2013). For the HEFA pathway, feedstock costs are considerably higher than the cost of fossil-derived jet fuel. The likely cost of advanced bio-jet alternatives based on biomass or algal feedstocks is less clear as these are not currently available at commercial quantities.

Although several technical and economic analyses have assessed the biomass-to-bio-jet pathways, many assumptions were required because of limited data and experience (de Jong *et al*., 2015). Most of these assessments have shown that it would be difficult to compete on costs with fossil fuels, despite several of these analyses estimating the cost of operating multiple and more established plants, and therefore benefitting from economies of scale. Current experience with cellulosic ethanol plants has shown that these initial pioneer plants are far more costly to build and run than conventional ethanol plants.

In the U.S., however, HEFA diesel is competitively priced once government policy support is included. Thus, in at least that country, the cost challenge can be addressed through policy measures.

15 One oil barrel is defined as 42 gallons, and about 159 Ls.

Potential and Barriers

The greatest potential of bio-jet fuel lies in its ability to significantly reduce GHG emissions in the aviation sector and positively impact climate change. This is one of the most important considerations for their development. The strong and ongoing commitment of the aviation sector and the active involvement of an increasing numbers of stakeholders such as airlines and many aviation organisations to develop bio-jet through voluntary initiatives has been a major driving force behind bio-jet development and consumption.[16] Moreover, the number of commercial flights using bio-jet has increased significantly over the last few years, and a downstream supply chain has developed in some places.

Oslo's Gardermoen airport now offers bio-jet through its hydrant fuel-supply system. Recent bio-jet initiatives at other airports in Los Angeles, in the U.S., and in Karlstad, Sweden, have further helped demonstrate proof of concept and can serve as a model for expansion. Positive trends toward overcoming remaining technical obstacles include ongoing research and development and the proposed construction of several new facilities. There has been significant progress in ASTM certification of more bio-jet pathways over the past few years, and the approval process is now faster.

However, the cost of bio-jet is one of the most daunting barriers. Although ongoing low oil prices will likely delay the development of some bio-jet technologies and projects, lower oil prices might be less of an issue for aviation biofuels than for other sectors, because it is in the industry's best interest to find long-term solutions. However, when oil prices are at about USD 50 per barrel (USD 0.36/L) bio-jet is significantly more expensive, and the price gap will be difficult to close. Airlines generally have low profit margins, and do not generally consider themselves able to pay a premium for fuel. This will make it difficult for the airline industry to reach carbon neutrality by 2020. This means that policy measures could be crucial to promote the production and consumption of bio-jet fuels.

The lack of mature technologies is also a significant barrier. The HEFA pathway is the only mature process, but the cost of the oleochemical feedstock is high, at about 80% of the cost of making bio-jet. The cost of vegetable oils has historically tracked the price of oil, making it likely that feedstock costs will always be challenging.

16 The ICAO Global Framework for Alternative Aviation Fuels (GFAAF) can be consulted for more details on initiatives and investments. www.icao.int/environmental-protection/gfaaf/Pages/default.aspx

Alternative feedstocks that are considered more sustainable will likely suffer from a lack of availability, preventing significant production increases. They include UCO, tallow, tall oil, and non-edible crops such as camelina. Some time would also be needed to develop and optimise yields and new supply chains for crop feedstocks. As well, the potential is finite to increase the supply of other oleochemical feedstocks, such as those just mentioned or from residues from palm-oil processing and other industries.

Another challenge is that any of these options will put bio-jet in direct competition with the current biodiesel industry, where there is more demand and more-developed supply chains. This suggests that there won't be enough bio-jet to achieve GHG-reduction goals unless at least one of the lignocellulose-to-bio-jet pathways, such as SIP or ATJ, are commercialised.

The cost of the lignocellulose feedstocks should be lower, and not as closely correlated to oil prices. Availability is expected to be much greater. However, biomass-feedstock supply chains still need to be developed and optimised, as is underway in the cellulosic-ethanol industry. The global forest-products sector also has well-established supply chains, but these have mainly focused on timber and pulp-and-paper products.

Over the last 10 to 15 years, global wood-pellets supply chains have been developed, primarily based on forest and mill residues. The lower prices that the forest sector typically obtains when selling energy products or carriers such as pellets (as compared to lumber or pulp) are an example of the problems of both moving biomass over longer distances and the difficulty in making this a profitable activity without policy support. To be economically attractive, bio-jet will likely have to be produced from low-value residues and waste from forests, agriculture or MSW. Analysis has shown that the minimum sale price for bio-jet is very sensitive to the cost of feedstock, so optimisation of these supply chains will be essential. Another significant near-term barrier is the limited supply of commercially available bio-jet, resulting in small batch deliveries to aircraft distribution is done through an airport's hydrant system.

The use of oleochemical feedstocks such as vegetable oils or animal fats to make bio-jet will result in direct competition with the current biodiesel industry

These challenges highlight the importance of policy support for bio-jet and its supply chains. Incentives will be required to bridge the price gap between fossil-derived jet fuel and bio-jet. Bio-jet. There are some policy supports in place that can be replicated elsewhere, such as in the U.S., where bio-jet is eligible for renewable identification numbers (RINs) via the U.S. Renewable Fuel Standard, under existing categories D4, D5 or D7. This is a strong incentive for bio-jet production, but may not be sufficient because the RIN value would be the same as for other advanced fuels in these categories, such as biomass-derived diesel. As a high specification fuel, bio-jet requires additional processing for its production, thus making it more costly to produce. Bio-jet fuels are unlikely to compete with advanced biofuels under these categories without specific incentives designed for them. An example from The Netherlands is the expanded use of "biotickets" for bio-jet (Hamelinck et al., 2013).[17]

Two other significant barriers remain. One is the international nature of aviation, with regulation of emissions handled by the ICAO instead of at a national level. The one exception, albeit at a regional level, is the EU Emissions Trading System (ETS), which covers aviation emissions within the EU. Although this arrangement could possibly result in a sector-wide approach, progress has been slow. The ICAO recently agreed to a CO_2 standard for aircraft, and an agreement on global market-based measures will be implemented by 2020. This means that regulation of sector emissions has been delayed until then, along with the creation of incentives to use bio-jet fuels.

The second significant barrier to bio-jet development is the limited ability of individual countries to create national policies that can incentivise bio-jet development at an international level. For example, fuel for international flights is not usually taxed, so tax credits are not an option as an incentive. As a result, novel and internationally relevant policy approaches are required.

17 The recent ILUC directive amended the European Fuel Quality Directive (FQD) such that member states may permit aviation biofuels to be used to fulfil the biofuel target as specified in the Renewable Energy Directive (the same structure that is used in The Netherlands). See also Source: Directive 2015/153 amending FQD (98/70/EC) and the RED (2009/28/EC). http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015L1513&from=EN (article 2a)

Process and technology status

The aviation sector requires drop-in bio-jet fuels that are functionally equivalent to fossil fuel and that are fully compatible with the existing infrastructure (IEA Bioenergy, 2014). Jet fuel is a high-specification fuel that must meet standards as defined in ASTM D6155 for Jet A1, or by the Ministry of Defence Standard 91-91 in the UK. Bio-jet fuel must meet these same standards and in addition have an ASTM D7566 certification.

In addition to the four pathways that certified to date, several others are in the process, such as hydrotreated depolymerised cellulosic jet and green diesel (HDRD or HRD). The ASTM certification procedure is rigorous and can take years and millions of U.S. dollars to complete.

The four certified pathways to produce bio-jet fuels are described here and shown in Figure 2:

- **HEFA:** oleochemical conversion processes, such as hydro-processing of lipid feedstocks obtained from oilseed crops, algae or tallow

- **FT:** thermochemical conversion processes, such as the conversion of biomass to fluid intermediates (gas or liquid) followed by catalytic upgrading and hydroprocessing to hydrocarbon fuels

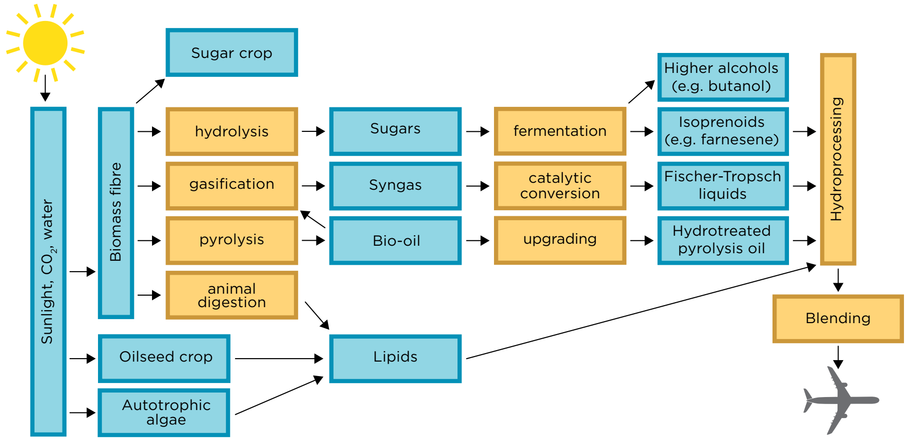
- **SIP:** biochemical conversion processes, such as the biological conversion of biomass (sugars, starches or lignocellulose-derived feedstocks) to longer chain alcohols and hydrocarbons

- **ATJ**: A fourth category includes "hybrid" thermochemical or biochemical technologies; the fermentation of synthesis gas; and catalytic reforming of sugars or carbohydrates

For technologies of any type, a technology readiness- level scale is often used to determine the maturity of a technology and its closeness to market. The Commercial Aviation Alternative Fuels Initiative's fuel readiness level (FRL) scale performs this function for bio-jet pathways. The scale rates ASTM-certified fuels at FRL7 or higher.

A recent study by Mawhood *et al*. (2016) evaluated pathways to bio-jet against this scale and concluded that HEFA was at FRL9, FT at FRL7 to FRL8, SIP between FRL5 and FRL7, and others in a range from four to six. Based on this scale, the recent ASTM certification of ATJ would give it a rating of FRL7. What these ratings do not capture, however, is the commercial viability of a certain pathway. As noted earlier, FT bio-jet was certified based on using coal as the feedstock, not biomass. While the feedstock does not affect fuel properties, it does have an impact on production potential, production

Figure 2: A simplified schematic diagram of different technology pathways to bio-jet fuel



cost and technology readiness (RAND Corporation and Massachusetts Institute of Technology, 2009). It will also significantly impact the potential of the fuel to reduce GHG emissions.

This leaves questions about the FT pathway, for which certification used coal as a feedstock. This is the closest to commercialisation among the advanced pathways based on the FRL classification, but significant challenges still must be resolved if the method is to be useful in meeting emissions-reduction targets. A recent report by France's Académie des Technologies and Académie de l'Air et de l'Espace concluded that vegetable oil-based HEFA bio-jet is likely to be the only economically viable option in the near future.[18]

A key aspect of bio-jet production is the requirement for hydrogen (H_2) to upgrade oxygen-rich carbohydrate, lignin or lipid feedstocks to hydrogen-rich hydrocarbons that are functionally equivalent to petroleum-derived jet fuel. Thus, some type of hydroprocessing step will likely be required for most bio-jet fuel technology platforms, with external sources of hydrogen used to remove oxygen in the form of water from the starting material, or to saturate double bonds in a final polishing step (IEA Bioenergy, 2014). Processes that do not require hydrogen can be used, including chemical and biological processes, but yields will be smaller because of the consumption of a portion of the feedstock.

18 www.biofuelsdigest.com/bdigest/2015/10/14/french-study-says-commercial-aviation-biofuel-still-a-ways-off/

The amount of hydrogen needed to produce bio-jet from a feedstock is illustrated by the effective hydrogen to carbon ratio, Heff/C, in the biomass feedstocks. This hydrogen-to-carbon ratio provides a useful metric to better understand and compare the technical and economic challenges of the various drop-in biofuel processes using different types of biomass feedstocks (IEA Bioenergy, 2014).

This staircase approach, which involves assessing how much oxygen needs to be displaced by hydrogen, establishes a ranking of feedstocks by how "easy" they are to upgrade. This shows that oils and fats need the least hydrogen, and are therefore the easiest, whereas sugars and lignocellulosic biomass need the most.

The amount required is important to determine the overall impact on GHG emissions because most hydrogen is produced by the reforming of natural gas, making fossil-fuel consumption a part of the process.

Technologies for oloeochemical conversion processes

The dominant HEFA pathway uses oil and fat feedstocks such as palm oil, used cooking oil and tallow. These "fat-derived" or "oleochemical-derived" drop-in biofuels are often referred to as HEFA, but are also called hydrotreated vegetable oil biofuels (HVO). This technology is mature and currently operates at a commercial scale.

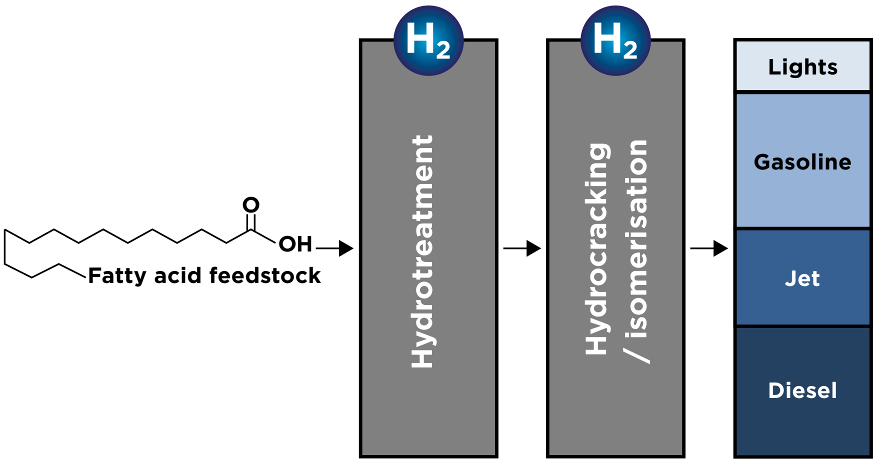
HEFA is notably distinct from fatty acid methyl ester (FAME) biodiesels, which retain an oxygen ester and are therefore too oxygenated to be used as a drop-in biofuel. Almost all of the world's commercial plants that are able to make HEFA are currently producing mostly HEFA diesel; but as of 2016, California's AltAir Fuels had become the first dedicated HEFA bio-jet production facility. Notably, AltAir's production process results in a mixture of hydrocarbon molecules from which several products, such as renewable diesel, bio-jet and naphtha, must be separated.

The two main technologies used commercially to make HEFA are Neste's NEXBTL and UOP and Eni's EcofiningTM processes. The EcofiningTM technology has been licensed by several companies and is used in a number of facilities.

Vegetable oils contain about 10 wt% oxygen, which must be removed to produce drop-in HEFA biofuels. Hydrotreating of vegetable oils to remove this oxygen typically consumes about 3 wt% of hydrogen. Alternative deoxygenation processes that require less or no hydrogen also produce less HEFA because of carbon losses as part of the process (IEA Bioenergy, 2014).

Trials have shown that HVO biofuels can also be produced by co-processing oleochemical feeds with petroleum

Figure 3: Basic diagram of the oleochemical conversion pathway



feeds in modern oil refineries, although challenges remain (IEA Bioenergy, 2014). Chevron, Phillips66 and BP have an ASTM D7566 application underway to certify jet fuel produced through the co-processing of vegetable oils using this method at a 5% concentration.[19]

The vast majority of the drop-in biofuels in aviation trials have used HEFA bio-jet primarily because the technology is mature and ASTM approved, but unless there are incentives to offset the high price, oil- and fat-based feedstocks are more likely to be converted to conventional FAME biodiesel. Another obstacle to scaling up the HEFA pathway is that increasing the fraction of jet-fuel range products produced from oleochemical feedstocks requires higher hydrogen inputs (more extensive hydrocracking) and also results in lower yields. These extra costs must be considered when developing strategies to promote increased bio-jet production (IEA Bioenergy, 2014). The proposed use of HEFA diesel as a bio-jet blend will minimise additional processing costs.

Vegetable-oil feedstocks require more land to produce than other feedstock types. Algae and non-food crops such as camelina, grown as a rotation crop, are examples of oleochemical feedstocks that require less land. These have been assessed by various initiatives, such as the U.S. Department of Agriculture "farm-to-fly" program; the U.S. Department of Energy's National Alliance for Advanced Biofuels and Bioproducts consortium, which is now complete; the European 7th Programme for Research and Innovation; Horizon 2020; and the "Flightpath" programs. Cooking oil and tallow are much more sustainable, but availability is limited. In the short- to mid-term neither have the potential to contribute significantly to any increase in the production of bio-jet. The U.S. Environmental Protection Agency has estimated that about 3 bln gallons (11.4 bln L) of used cooking oil is produced each year in the U.S., resulting in a theoretical yield of about 9 bln L of HEFA bio-jet, based on 1.2:1 feedstock to fuel ratio. However, much of this feedstock is currently used to make biodiesel.

One strategy for improving costs of bio-jet based on the oleochemical conversion route is the use of HDRD diesel as a jet substitute. This also involves the upgrading of vegetable oils. Boeing and Neste have applied for ASTM certification under ASTM D7566 to blend small amounts of vegetable oil with ordinary jet fuel[20]. Boeing completed a test flight using a 15% blend of HDRD in December 2014. Although no information is available on costs, this blend should be cheaper to produce than HEFA bio-jet, as the blend is likely to require less processing and result in potentially higher yields. The process is similar to current HEFA diesel production.

19 www.caafi.org/news/News.aspx?id=10251

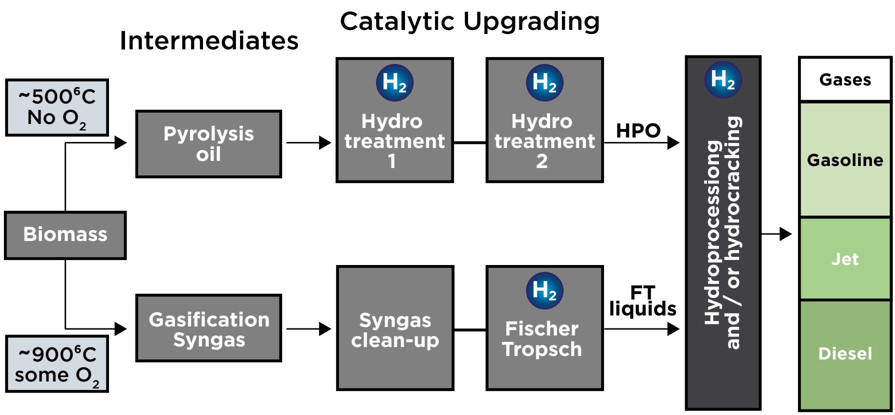
20 www.neste.com/fi/en/neste-and-boeing-lead-industry-commercialization-renewable-aviation-fuels

It differs in that longer carbon-chain lengths from vegetable oils are not cracked into shorter jet-range molecules. Instead increased isomerisation is used to improve the cold flow properties of the blend, allowing low bio-jet blends that still meet the overall specifications for jet fuel.

Thermochemical routes to turn biomass into bio-jet fuel

The major challenges for thermochemical routes to bio-jet differ mainly in conversion-process efficiency and technology risks, although feedstock choices can also result in qualities in the end product. Thermochemical routes used to turn biomass into bio-jet involve the production of three main products, in different ratios: bio-oil, synthesis gas and char. The two main thermochemical routes to bio-jet are gasification and pyrolysis, and hydrothermal liquefaction (HTL). The FT process uses gasification combined with synthesis to produce bio-jet. Several commercial facilities based on gasification-FT are planned, and this pathway is discussed in more detail below. The pyrolysis route to bio-jet is known as HDCJ (hydrotreated depolymerised cellulosic jet). An ASTM application for HDCJ was initiated by KiOR, but the company is now in bankruptcy, creating a setback for the certification of this pathway.

Figure 4: Schematic of thermochemical conversion routes



Gasification

Gasification involves the heating of small feedstock particles at high temperatures in a controlled-oxygen environment to produce synthesis gas, which is comprised of mostly H_2 and carbon monoxide and typically called syngas. Syngas converts to numerous gaseous and liquid chemicals or fuels via the FT process using catalysts. This process produces a mixture of hydrocarbon molecules from which various fuels and chemicals can be extracted.

Gasification and FT have been used since the 1980s by South Africa's Sasol company to convert coal into fuels, at a current capacity of 160 000 barrels per day (b/d). The FT process is also used in the world's largest natural gas-to-liquids plant, Shell's Pearl facility in Qatar. It was completed in 2011 and produces 140 000 b/d of fuels (IEA Bioenergy, 2014). Although bio-jet could potentially be produced via this process, using biomasses such as black liquor or bio-oil as a feedstock, various challenges have prevented this on a commercial basis.

Bio-jet produced via FT was certified by ASTM in 2009, at up to 50% of a blend with conventional jet fuel, but it was produced using coal as the feedstock and not biomass. The feedstock that is used to make FT syngas can result in different products during and after gasification. This significantly influences the composition of the syngas. For efficient fuel production, a desirable syngas should be a mixture of H_2 and CO only, with all contaminants removed.

Gasification of biomass typically results in considerable tar formation that needs to be cleaned up, and the high oxygen content of biomass impacts the ratio of H_2 to CO in the synthesis gas. As a result, biomass-derived syngas is less energy dense than syngas derived from natural gas, has a lower ratio of hydrogen to carbon, and contains more impurities. Typically, biomass and MSW-derived syngas needs to be enriched in hydrogen and cleaned of impurities such as tars, nitrogen and other atoms comprised of anything other than carbon or hydrogen. These impurities can deactivate the synthesis catalysts. Although cleaning syngas is technically possible, it has proven to be costly. Plasma gasification is another way to produce a very clean syngas, but has also proven to be significantly more expensive.

To date, gasification technologies have entailed high capital costs to both gasify the biomass and convert the resulting syngas to FT liquids or partially oxygenated liquid hydrocarbon products such as mixed alcohols (IEA Bioenergy, 2014). These types of coal- or natural gas-fed facilities have been built at a large scale in the hopes of capturing economies of scale. The capital cost estimates for a first-of-its-kind commercial gasification-based facility range from USD 600 m to USD 900 m, and would typically have the capacity to produce 2 000 t per day of dry biomass (Swanson *et al*., 2010). Although this is a significantly smaller size than current facilities based on coal and natural gas, logistics challenges will be likely because biomass is a less energy-dense feedstock.

Some of these anticipated supply-chain challenges can be mitigated through the use of alternative feedstocks such as pyrolysis bio-oils, which are more energy dense than wood. Because a range of hydrocarbon molecules are produced by the FT process, large-scale facilities are also in a better position to market the multiple commercial products created, thus improving the overall economics.

Current FT technology results in a maximum of about 40% of the final product comprised of bio-jet fuel and middle distillates, requiring the marketing of the other 60% of the output.

Commercial biomass-gasification facilities under construction include those of Fulcrum Bioenergy and Red Rock Biofuels, in U.S. Kaidi has proposed building an FT facility in Finland. These pioneer plants should provide invaluable insights and lessons for future investment. Many people believe that costs for the FT route could fall considerably as the technology matures. Fulcrum Bioenergy claims to be able to produce FT transportation fuel at less than USD 1 per gallon[21] (USD 0.26/L) using MSW as a feedstock.

A proposal from Solena and British Airways to use MSW in a gasification process was recently cancelled. Solena hoped to use plasma gasification technology that was likely to cost significantly more than what Fulcrum will use. Red Rock Biofuels plans to use woody biomass as well as a different FT technology (from Velocys).

21 www.fulcrum-bioenergy.com/benefits/low-cost-producer/

Pyrolysis and hydrothermal liquefaction (HTL)

Fast pyrolysis exposes small biomass particles of about 3 mm in length to heat at 500°C for a few seconds to produce a bio-oil with up to 75 wt% yield (IEA Bioenergy, 2014). Although companies such as Ensyn in Canada have been producing fast-pyrolysis bio-oils for many years, these have mainly been used in niche applications such as food flavouring.

Energy applications have been restricted to heavy fuel oil used in stationary heating, and in power-generating facilities. Although Ensyn[22] recently obtained regulatory approval for RFDiesel and RFGasoline, which are fuel products generated via co-processing in petrochemical refineries, no jet fuel has been produced this way.

In the Netherlands, BTG has commercialised the flash pyrolysis technology in its EMPYRO[23] project. As of late 2016, however, bio-oil was used to replace natural gas in a heating application in a milk factory. BTG has also been testing possible co-processing of bio-oil in a petroleum refinery.

The commercial production of bio-jet via the pyrolysis route is likely to be challenging because biocrudes derived from fast pyrolysis contain up to 40% oxygen, similar to the biomass itself. This necessitates extensive upgrading to produce bio-jet, which is typically achieved through hydroprocessing. These processing costs, as well as the need for external hydrogen, represent a large proportion of equipment and production costs (Jones *et al*., 2009).

A further challenge to the hydroprocessing of pyrolysis oils is the cost and stability of the catalysts that are required.

A potential advantage of the pyrolysis approach to bio-jet production is that it can be done in existing oil refineries, which reduces the need for capital to build a dedicated facility.

Similarly, significant savings might be achieved by directly sourcing hydrogen from an oil refinery and, in the longer term, through using existing processing units.

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

23 www.empyroproject.eu/

Co-processing in existing petroleum refineries is considered a key strategy for upgrading pyrolysis-derived bio-oils, but comes with some technical challenges. These include selecting the point of insertion, the extent to which upgrading is required prior to insertion and the disparate types of catalysts needed for bio-oils compared with those used in oil refining. Refinery-insertion strategies should be synergistically beneficial but are likely more technically challenging than is generally acknowledged (IEA Bioenergy, 2014).

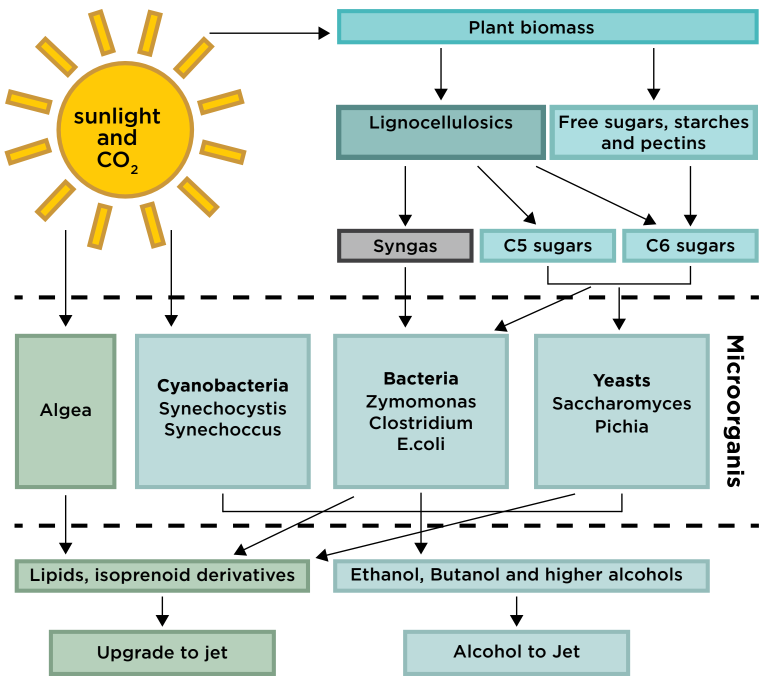
Catalytic pyrolysis or processes such as HTL can produce a bio-oil intermediate with significantly lower oxygen content, at less than 10%. That would be easier to upgrade to produce fuels, including bio-jet.

Although some studies have indicated that this method could potentially produce the lowest-cost bio-jet (de Jong *et al.*, 2016), the high-pressure requirements of HTL during the production of biocrude will impact their potential for scale-up. While production of bio-oil via pyrolysis is at a commercial scale, HTL is currently just at the demonstration stage, as pioneered by Licella's Australian plant. Although there is a scarcity of reliable technical and economic analyses, a minimum fuel-selling price (MFSP) of USD 3.39 per gallon could be achieved when making diesel and gasoline via fast pyrolysis followed by upgrading (Jones *et al.*, 2013).

Biochemical routes to turn biomass into bio-jet fuel

Capital expenditure for biochemical routes to bio-jet are projected to be lower than those for thermochemical routes (IEA Bioenergy, 2014), but that benefit may be offset if the MFSP is higher, which is also expected (Table 2). In contrast to the more familiar sugar-to-ethanol fermentation route to bioethanol, advanced biological routes convert sugars to less oxygenated and more energy-dense molecules such as longer-chain alcohols like butanol and butanediol. Advanced biological routes can also convert sugars to larger hydrocarbon molecules such as isoprenoids and fatty acids (IEA Bioenergy, 2014). Amyris, using genetically engineered yeasts, converts sugars directly to renewable hydrocarbons such as farnesene. Farnesene can then be upgraded to farnesane through hydroprocessing, producing SIP. It is also known as the Direct Sugars to Hydrocarbons (DSHC) pathway. It received ASTM certification in 2014, provided it is used in a 10% blend with fossil-derived jet fuel.

Figure 5: Schematic overview: From microorganism to bio-jet fuel with various renewable feedstocks



Adapted from Weber et al. (2010)

Although butanol, n-butanol and isobutanol are oxygenated and thus cannot be considered to be fully "drop-in" biofuels, they are less oxygenated and less hydrophilic than ethanol and can be used to produce bio-jet fuel through the ATJ pathway. Gevo recently obtained ASTM certification for its bio-jet fuel produced from isobutanol, which Alaska Air has used in a commercial flight.

The potential to use existing ethanol facilities lies in the ability to replace the existing yeasts that produce ethanol with alternative microorganisms that could instead make bio-jet. Because some of the biological intermediates such as farnesene are quite hydrophobic they should in theory be more readily recoverable from the aqueous fermentation broths. Nevertheless, the recovery of these molecules from the fermentation broth has been more challenging than predicted because of intracellular expression of hydrophobic metabolites. For butanol, fermentation titers are typically well below the concentration that induces phase separation, which ranges from 70 g/L of butanol to 80 g/L (IEA Bioenergy, 2014).

Biochemical-based bio-jet pathways can produce highly reduced biohydrocarbon molecules such as sesquiterpenes and fatty acids based on the used microorganism, which accordingly decrease the degree of final hydroprocessing required to meet jet-fuel specifications. Even still, advanced biological pathways require more energy and carbon-intensive metabolic processes than required in ethanol production in order to decrease feedstock sugars.

Given the potential commercialisation scale, conventional ethanalogenic yeast fermentations could achieve a higher order of magnitude than the product yield for fermentation-derived bio-jet. Furthermore, biochemical-based bio-jet platforms are relatively pure, and functionalised long carbon-chain molecules can be produced. This is an advantage over thermochemical-based processes (IEA Bioenergy, 2014).

The production of bio-jet would not be the most profitable use of biochemically processed biomass and sugars. Products such as carboxylic acids, alcohols and polyols can generate higher profits because there are fewer processing steps, lower NADPH requirements, and less hydrogen consumption. Less-oxygenated microbial metabolites with potential as drop-in biofuel intermediates are already being sold in the value-added chemicals and cosmetics markets, such as Amyris's farnesene and Gevo's or Butamax's butanol (IEA Bioenergy, 2014). The market for biochemical drop-in products is highly competitive and growing. Tthe volume of biochemical drop-in products in the market is expected to increase by between 10 Mt and 50 Mt annually to 2020, which is equal to the current markets size of biofuels (Lux Research, 2010; Higson, 2011; Bomgardner, 2012). Incentives will be required for commercial entities to concentrate on drop-in fuels until the market is saturated.

Hybrid conversion processes

Hybrid conversion processes can combine a mixture of the above methods. For example, the ATJ process can combine biochemical production of alcohol, through fermentation of sugars or conversion of syngas from gasification and catalytic conversion of the alcohol to bio-jet. Another example of a hybrid process is Virent's aqueous phase reforming. This process uses feedstock sugars potentially derived through biochemical conversion of lignocellulosic feedstocks, while synthesis takes place via catalysis.

Preparing for take-off: Capacity and market potential

Though the vast majority of commercial volumes of bio-jet fuels are produced through the HEFA pathway, the main product in all but one of these facilities is HEFA diesel. Bio-jet production is a small fraction of total plant capacity (Table 1). Only the AltAir facility in Paramount, California, is the situation there reverse, with the bulk of production accounted for by bio-jet, and HEFA diesel a smaller-volume output (Table 1).[24] The operational capacity of the world's current HEFA facilities is about 4.3 bln L/y. Even if all of this capacity were to be diverted to bio-jet production, supply would amount to less than 1.5% of the world's jet fuel requirements.

HEFA is typically used as a general term, with HEFA bio-jet or HEFA-SPK used to denote bio-jet. As there is some overlap in carbon-chain lengths, the bio-jet fraction within HEFA can also be sold as diesel. The nature of the products formed are also influenced by the extent of hydrocracking, which can result in the formation of smaller naphtha products. The type of technology used to produce HEFA fuels can also have an impact on the nature and ratio of products obtained. The NEXBTL and Ecofining™ technologies are the two most common technologies. Ecofining™ was designed to maximise the ratio of bio-jet or renewable diesel yields, depending on demand. The fractionation of the bio-jet from other products usually requires a distillation process, which adds additional capital and operational cost.

Boeing has applied to ASTM for certification of a blend that includes HDRD and renewable diesel with jet fuel. Boeing has tested blends of up to 15% of this fuel in a demonstration flight. If approved, this pathway could have a significant impact on bio-jet production capacity because renewable diesel with good cold-flow properties could also be used as a bio-jet component. However, what types of blends might be approved was not yet clear in late 2016. One challenge is that diesel molecules have longer carbon chains than jet, which impacts their cold-flow properties. Currently, commercial diesel products are broadly differentiated into summer, winter and arctic fuels. Winter and arctic diesels have improved cold-flow properties because of blending with additives or through increased isomerisation of hydrocarbons. These types of diesels will likely be the most suitable for blending into jet fuel.

24 Light gases are also produced, mainly propane and naphtha. Larger volumes of naphtha are produced when bio-jet is maximised as this involves hydrocracking of diesel range molecules.

Table 1: Companies producing HEFA fuels (mainly renewable diesel)

Company	Location	Technology	Feedstock	Capacity	Status
Neste	Rotterdam, Netherlands	NEXBTL	Vegetable oils, UCO and animal fats	1.26 bln L/y	Operational
Neste	Singapore	NEXBTL	Vegetable oils, UCO and animal fats	1.26 bln L/y	Operational
Neste	Porvoo, Finland	NEXBTL	Vegetable oils, UCO and animal fats	240 m L/y	Operational
Neste	Porvoo 2, Finland	NEXBTL	Vegetable oils, UCO and animal fat	240 m L/y	Operational
ENI	Venice, Italy	Ecofining™	Vegetable oils	450 m L/y	Operational
Diamond Green Diesel	Norco, Louisiana, U.S.	Ecofining™	Vegetable oils, UCO and animal fats	500 m L/y	Operational
UPM	Lappeenranta, Finland	UPM Bioverno	Crude tall oil	120m L/y	Operational
AltAir	Paramount, California, U.S.	Ecofining™	Non-edible oils and waste	150 m L/y	Operational
Renewable Energy Grouo	Geismar, Louisiana, U.S.	Developed by Dynamic Fuels LLC	High and low free fatty acid feedstocks	315 m L/y	Operational
Emerald Biofuels	Port Arthur, Texas, U.S.	Ecofining™	Vegetable oils	330 m L/y	Planned Construction

Given the operational capacity of the world's current HEFA facilities, at about 4.3 bln L/y, supply would amount to less than 1.5% of the world's jet fuel requirements if all facilities produced only bio-jet. Commercial capacity is even smaller for FT, with two planned facilities with a combined 82 m L/y, and another proposed at 1 bln L/y.

Current and future foreseen production capacity is difficult to determine as only one company, Amyris, produces this potential biofuel in sizable quantities, at its plant in Brotas, Brazil. Due to the high value of farnesene as a biochemical, cosmetics ingredient, and lubricant feedstock, most the farnesene that is currently produced is sold into non-bio-jet markets.

Although the ATJ pathway received certification based on Gevo's isobutanol, there is currently no integrated commercial facility for bio-jet production using this route.[25] The EU, under FP7,[26] is supporting the development of two demonstration projects. One will produce bio-jet from ethanol using Swedish Biofuels' technology and the other will produce bio-jet from the lignin fraction of a cellulosic ethanol plant using Biochemtex' technology. The former will have a capacity of 10 ML/y. of bio-jet, and the latter will be smaller.

25 Gevo's production of isobutanol and the subsequent conversion to bio-jet took place at different locations.

26 https://ec.europa.eu/research/fp7/index_en.cfm

The operational capacity of the world's current HEFA facilities is about 4.3 bn L. Even if all of this capacity was diverted to bio-jet production, it would provide less than 1.5% of the world's jet fuel requirements

Jet fuel consumption and future projections

In 2014, global consumption of jet fuel was 5.4 m b/d (314 bln L/y) (IEA, 2015). Aviation-sector growth is expected to increase, and jet-fuel consumption along with it, however projections of future jet-fuel demand differ. The IAE expects demand to reach 9 m b/d (522 bln L/y) by 2040 (IEA, 2015). The ICAO forecasts a range from 496 bln L/y to 691 bln L/y (ICAO, 2016) by 2040. This would be an increase of at least 58%, with the potential for demand to more than double.

Over the last few years the aviation sector has outlined sector-specific GHG emissions-reduction targets, including carbon-neutral growth by 2020 and a 50% reduction in carbon emissions relative to 2005 by 2050 (IATA, 2015). Although there is increasing recognition that bio-jet fuels will have to play a significant role in meeting these targets, there is very limited information on the projected bio-jet fuel volumes that will be required under these scenarios. The IATA Sustainable Aviation Fuel Roadmap (IATA, 2015) lists some of the aspirational bio-jet goals and targets adopted by some companies, countries and international bodies. For example, the U.S. Federal Aviation Administration aspires to a target of 1 bln gallons (3.758 bln L) of bio-jet by 2018.

Boeing set a target of 1% for 2016, while Australia has aimed for 50% by 2050, the EU 2.5 bln L by 2020 and 40% by 2050, Germany 10% by 2025, Indonesia 2% by 2018, and Israel 20% by 2025. However, the nearer-term targets are unlikely to be met, as expansion of production capacity has been much slower than expected.

Recent reports have described initiatives in the bio-jet arena including IATA's annual Reports on Alternative Fuels publication (IATA, 2014 and 2016) and its Sustainable Aviation Fuel Roadmap, and the earlier Ecofys report on Biofuels for Aviation (Ecofys, 2013). The present review highlights the latest developments, subsequent to those reports.

Despite increasing recognition that bio-jet fuels will be crucial to meet targets, there is only limited information on the projected volumes required

The early initiatives that used to assess the viability of bio-jet use were typically based on single demonstration flights that were supported by airlines or original equipment manufacturers (OEMs), and more assessments since then have helped to establish "proof of concept' for bio-jet. Considerations included supply-chain initiatives and feasibility studies that also addressed feedstock, technology, distribution and policy issues.

Stakeholders now include OEMs, airlines, aviation-industry organisations, fuel producers, feedstock producers, airports and facilitators such as SkyNRG. The predominant trend has been to establish voluntary initiatives at local and regional levels to establish bio-jet supply chains at specific airports. SkyNRG's bioport concept is an example of this type of initiative.

Several OEMs have been instrumental in the development of bio-jet fuels, with the two leading manufacturers, Airbus and Boeing, making significant contributions. Airbus has developed programmes in Australia, Brazil, Qatar, Romania and Spain, and has partnered with China's Tsinghua University and the China Petroleum and Chemical Corporation (Sinopec) to explore bio-jet development in China. Airbus has also carried out numerous test flights using bio-jet fuels.[27].

Airlines and commercial-freight companies also promote bio-jet fuels, primarily as customers through trial flights or through off-take agreements. Participants in these efforts include Aeromexico, Alaska Airlines, British Midland, FedEx, Finnair, Gol, KLM, Lufthansa, Qatar Airways, Scandinavian Airlines (SAS), Southwest Airlines and others. Airlines that have invested in research and development and in supporting companies commercialising bio-jet production include Cathay Pacific, Etihad, Qatar Airways and Etihad.[28]

One high-profile initiative has been the U.S. Navy's launch of its Great Green Fleet on 21 January 2016. Although only a 10% blend of bio-jet fuel was used, as opposed to the 50% target proposed in 2009 seven years ago, the goal of a 50% "green fuel" remains the Navy's ultimate objective.[29]

Policy support is widely recognised as essential if bio-jet deployment is to be successful. According to the IATA, "voluntary instruments are likely to be most effective when used in synergy with, or complementary to, other public instruments" (IATA, 2015). The Indonesian government's announcement of a mandate for bio-jet is one example of public-policy support that could have a significant impact on bio-jet development. However on a global basis there have been very limited government efforts to develop and implement the types of policies that have been successful in promoting road-transport biofuels. These include

27 www.airbus.com/innovation/future-by-airbus/future-energy-sources/sustainable-aviation-fuel/

28 www.biofuelsdigest.com/bdigest/2015/10/19/the-airlines-whos-doing-what-in-aviation-biofuels/

29 hwww.navytimes.com/story/military/2016/01/20/stennis-strike-group-sets-sail-10-percent-beef-fat-fuel-blend/79054624/

mandates, tax incentives and subsidies. As will be further discussed in the policy section of this brief, this low level of government policy support is one of the main reasons why there has been limited development and deployment of bio-jet. The lack of direct government involvement might be partially due to the international nature of aviation and the legal role of ICAO.

Market prospects

Projections are for the biggest increases in aviation-fuel demand in Asia, Africa, Latin America and the Middle East (IEA, 2015; Boeing, 2015). This market expansion will be driven by increased passenger and cargo traffic, with the developing economies of China and India leading the way.

Although bio-jet production in these regions would be influenced by supporting policies where applicable, feedstock availability is also likely to be a relevant factor. In the same way that bioethanol development in Brazil and the U.S. was helped by the availability of sugar and starch, respectively, as feedstocks, bio-jet development is likely to follow a similar trend. As noted, bio-jet will probably be based in the near to mid-term on oleochemical feedstocks such as oils and fats. Those regions that have an abundance of cheap oils and fats suitable as feedstocks for the HEFA pathway should initially be in a better position to establish and expand bio-jet production, distribution and use. Countries such as Indonesia could develop bio-jet production capacity based on domestic production of palm oil, instead of exporting the oil to facilities in other countries, such as Neste's in Rotterdam. However, issues such as sustainability and indirect land-use change must be addressed.

For advanced bio-jet using lignocellulosic or algal feedstocks, potential challenges as the relevant technologies mature include feedstock availability, cost and sustainability. Facilities based on thermochemical technologies and woody biomass could be based in regions with an ample supply of feedstock, such as mill and forest residues, eliminating or minimising costs for transporting them. Optimal spots for biochemical technologies using advanced fermentation based on sugars. Jurisdictions where sugars or starches are available in large quantities, such as Brazil and the U.S., will be ideal for facilities using advanced fermentation pathways.

Performance and cost

If Bio-jet fuels are to be used in mass quantities by the aviation industry they must conform to strict specifications to be certified under ASTM standard D7566, and their performance will have to be equal to or better than conventional jet fuel. In some cases, however, it may offer an improvement to conventional fuel, in part thanks to a lower sulphur content.[30]

The cost of bio-jet is difficult to determine, as this is not a readily available commodity, and contracts for purchase of volumes of bio-jet do not usually disclose the price. Existing analyses should be treated with caution, as assumptions will have been made that are not necessarily accurate, resulting in wide ranges for cost estimates, such as the common one that bio-jet currently costs anywhere from two to seven times more. Most analyses rely on estimates based on having multiple plants, which generally overestimate yields and underestimate capital costs, particularly for pioneer plants (de Jong *et al*., 2015).

Although the HEFA technology is commercially mature, costs will remain a significant challenge due to the high price of the feedstock, as well as availability and sustainability concerns.

The selling price of the vegetable oil feedstocks has historically been higher than the selling price of diesel and jet fuels (IEA Bioenergy, 2014). In April 2016, select vegetable oil prices per metric tonne were USD 799 for soybean oil, USD 727 for crude palm oil, and USD 811 for rapeseed. Sunflower oil cost USD 858, and palm kernel oil USD 1 289.[31] UCO, also called yellow grease, was trading at between USD 550 and USD 638 per metric tonne in June 2016.[32] Jet fuel in April 2016 cost about USD 400/t.[33]. Although alternative oil-rich crops such as camelina might overcome potential sustainability concerns, the cost of producing these types of oils is not clear.

Costs are difficult to determine, as bio-jet is not a readily available commodity, and prices for purchases by volume are not usually disclosed

A techno-economic analysis in 2015 calculated the MFSP for bio-jet via different conversion routes for multiple plants when using lignocellulosic feedstock, but relies on modelling studies because no actual data is available, unlike for HEFA bio-jet (de Jong *et al*. 2015). The two lignocellulosic substrates modelled,

30 www.biofuelsdigest.com/bdigest/2016/06/09/renewable-jet-fuel-why-everything-is-so-up-in-the-air-a-view-from-the-cockpit/?utm_campaign=shareaholic&utm_medium=email_this&utm_source=email

31 Oils and Fats International, May 2016 Vol 32(4). www.oilsandfatsinternational.com

32 www.ams.usda.gov/mnreports/lswagenergy.pdf

forest residues and wheat straw, were based on feedstock costs of EURO 95 per dry tonne (USD 106) for forest residues and EUR 190 per dry tonne (USD 212) for wheat straw. The difference in feedstock price resulted in a broad range of final MFSP values. As these estimates are based on European feedstock prices and infrastructure, costs in other geographical areas will vary substantially. Only lignocellulosic feedstocks were modelled, although ATJ and SIP can also utilise sugar or starch-based feedstocks.

Table 2: MFSP of bio-jet fuel based on technical and economic analysis

Conversion Process	Feedstock	MFSP bio-jet produced in multiple plants EUR per tonne
HEFA	(UCO)	1 350 (USD 1 518)
FT	Forest residues / wheat straw	1 800 – 2 650 (USD 2 024 - 2 980)
HTL	Forest residues / wheat straw	900 – 1 300 (USD 1 012 - 1 460)
Pyrolysis	Forest residues / wheat straw	1 300 – 1 850 (USD 1 460 - 2 080)
ATJ	Forest residues / wheat straw	2 400 – 3 500 (USD 2 700 - 3 935)
DSHC	Forest residues / wheat straw	4 800 – 6 400 (USD 5 397 - 7 196)

Source: de Jong et al. (2015)

The cost to establish a pioneer plant was assumed to be 50% higher than establishing multiple plants, with resulting economies of scale (de Jong *et al*. 2015). The study noted several potential ways to cut costs, such as using low-cost or negative-cost feedstocks such as MSW. In addition, cost savings can be achieved through co-location, co-processing or using existing infrastructure, particularly if output includes other products to sell. Maximising overall yield of the saleable product range will be key to the economics of any establishment, just as with petrochemicals refineries currently.

Several techno-economic analyses have determined capital costs associated with establishing biofuel facilities. De Jong *et al*. in 2015 reviewed several studies and normalised the values based on 2013 and an assumed output of 500 t of fuel per day. These studies are all based on production in multiple facilities.

Table 3: Summary of technologies, status and estimated capital costs

Conversion Process	Status	Capital cost in million -M EUR $_{2013}$
HEFA	Commercial	200 – 644 (USD 265 – 855)
Gasification - FT	Demonstration	327 – 1 186 (USD 434 – 1 575)
Pyrolysis & upgrading	Pilot / demo	156 – 482 (USD 207 – 640)
HTL & upgrading	Pilot / demo	273 – 513 (USD 362 – 681)
Alcohol to jet (ATJ) (from ethanol; excludes ethanol production)	Demo	68 – 72 (USD 90 – 96)
Advanced fermentation of sugars to hydrocarbons (farnesene)	Small commercial	292 (USD 388)
Ethanol production from agricultural residues (includes pre-treatment, enzymatic hydrolysis & fermentation)	Commercial	215 – 426 (USD 285 – 566)
Sugar extraction from agricultural residues (includes pre-treatment & enzymatic hydrolysis)	Commercial	206 (USD 274)

Based on normalised reported values from literature for 500 t of fuel per day, with figures based on 2013 values. The 2013 exchange rate was used to convert EUR to USD at a rate of EUR 0.753 to USD 1 (de Jong *et al*. 2015).

The estimated MFSPs indicate that bio-jet is likely to cost significantly more to produce than fossil jet fuel, highlighting the crucial role of policy makers to bridge this price gap. The IATA said in 2015 that sustainable aviation fuels are approximately two to seven times more expensive than fossil jet fuel (IATA, 2015). However, this gap is likely to drop due to investment in research and operator experience.

Potential and barriers

Life cycle analysis of bio-jet fuels shows they can reduce emissions by at least 50% when compared with fossil jet fuel, and by as much as 95% (IATA, 2015). The reduction rate varies according to the combinations of feedstocks and conversion technologies that are used. Their continued development and use should help the aviation sector achieve its climate change-mitigation goals.

Examples of development in bio-jet include technologies that are already commercial; the first dedicated bio-jet facility, AltAir Fuels, which is now operational; and Oslo's Gardermoen airport becoming the first to provide bio-jet through its hydrant system rather than in a segregated supply. More commercial facilities are under construction, and several new pathways are on the verge of receiving ASTM certification, expanding the potential commercial supply of bio-jet fuel. However, the market for bio-jet has been slow to develop, and remains available only in small volumes thanks primarily to high costs and a lack of public-policy support, but also because of technical challenges.

Policies to promote bio-jet production and consumption

Policy support has been instrumental in the global development of road-transportation biofuels, such as in Brazil, the U.S. and the EU. The two main policy drivers in those cases were energy security and climate-change mitigation. Policies have been predominantly developed at a national level, primarily based on regulatory instruments such as blending mandates or renewable volume obligations. Measures implemented include subsidies, tax credits, grants for research and development, and loan guarantees for building pioneer facilities. These policies led to the development and commercialisation of the current global biofuels industry, which produces over 120 bln L/y of bioethanol and biodiesel.

Policies at international level – Policies that have encouraged the development and use of biofuels for road transportation use have been established predominantly at a national or regional level, but the international nature of aviation requires approaches both international and national. At the international level, the ICAO plays a major role in global development of the aviation sector. It works with 191 member states and global aviation organisations to develop international standards and recommended practices (ICAO, 2016). The member states are obliged to reference those standards when developing their own legally enforceable national civil-aviation regulations.

In 2016, after many years of debate and planning, ICAO has agreed on a new GMBM, with a goal of implementing these measures by 2020. Such market-based mechanisms would provide the basis to set a price on emissions, seen as the primary means for emission reduction at the national and regional levels. GMBMs have been proposed as a way to bridge the time gap, by limiting carbon emissions while bio-jet fuels and other technologies are developed.

The extension of national and regional policies to international aviation will initially be limited to the EU, with other jurisdictions applying carbon taxes to domestic flights only. A sector-based policy approach for the whole industry has been emphasised to ensure competitiveness between airlines by maintaining a level playing field. The GMBM could achieve significant emissions reductions as the fuel efficiency of aircraft improve[33] and as bio-jet developments expand. However, whether these measures will serve as a major stimulus for bio-jet development remains to be seen. As stated by Hind, "Even adding the carbon cost to the price of jet fuel, it is far more economically advantageous to burn regular fuel and pay the carbon penalty than to switch to biofuel." (Hind, 2014). One tonne of jet fuel emits just over 3 t of carbon, which currently trades at about EUR 5/t of CO_2 under the EU ETS. Thus, paying the extra EUR 15 per tonne is considerably cheaper than purchasing bio-jet at two to seven times the price of jet fuel. While overall carbon-emissions reductions might be achieved through the purchase of offsets, this may not stimulate bio-jet development unless the price of carbon is significantly higher and additional policies are used.

At a national level bio-jet for domestic flights could be encouraged through various policies, but the promotion of bio-jet for international flights will likely only be stimulated via incentives rather than penalties. Commonly used incentives such as tax credits will not work because fuel for these flights is typically not taxed, whereas fuel for domestic flights is often taxed.

Policies to bridge the price gap between bio-jet and conventional jet fuel – Types of policy support that could work for bio-jet could come from the biofuels sector, where incentives have been an effective tool. Currently only the Netherlands and the U.S. have implemented policies that promote bio-jet production and use. Indonesia has announced a bio-jet mandate, which has yet to be implemented.

The Netherlands offers an incentive for biofuel development through its bioticket

33 Another important policy at ICAO level is the recently agreed CO_2 standard for aircraft.

system. This policy was extended to bio-jet in December of 2012 (Hamelinck *et al.*, 2013). For each volume of biofuel sold, a company receives a bioticket, which can be traded between companies to fulfil their obligations under the EU Renewable Energy Directive (RED) [34]or Fuel Quality Directive (FQD).[35] The value of the bioticket is based on the biodiesel market and there is not a special price for bio-jet. In addition, the EU has a system of double counting for biofuels from waste in the national mandate under the RED.

In 2013, the U.S. Environmental Protection Agency announced that bio-jet could qualify under the RIN system in categories D4, D5 or D7.[36] The generation of RINs can be an attractive incentive as the current value of potential RINs for bio-jet is more than USD 0.80 per RIN for each per gallon of fuel.

This makes the U.S. a favourable market for production and import of bio-jet as the RIN value can help bridge the price gap between bio-jet and fossil-derived jet fuel. However, in this particular case, bio-jet production and development will likely compete with the production of renewable diesel for the same RIN incentive. Renewable diesel is easier to make and sells at a higher price, making it considerably more attractive to produce.

The January 2016 multi-stakeholder initiative to deliver bio-jet via the airport hydrant supply at Oslo's Gardermoen airport is an example of successful support for bio-jet through policy. The Norwegian government offered bio-jet users a 25% reduction in landing fees, an exemption of biofuel from the Norwegian carbon tax that is applied to domestic flights, and an exemption or offset from the EU Emissions Trading Scheme for the amount of bio-jet used.[37]

Specific and additional policies are likely to be needed to support advanced bio-jet fuels that are made from lignocellulose or algal materials rather than from oleochemicals. This will be particularly important in countries that currently only promote conventional biofuels such as ethanol and biodiesel. Although specific incentives for bio-jet need to be developed, bio-jet should not be incentivised to the exclusion of the other products that are part of a fuel blend, as processes that maximise the production of bio-jet are likely to be less economic overall. Thus, while advanced biofuels deserve promotion, additional incentives are worth considering where bio-jet production might earn a premium.

34 https://ec.europa.eu/energy/en/topics/renewable-energy/renewable-energy-directive

35 http://ec.europa.eu/environment/air/transport/fuel.htm

36 www.platts.com/latest-news/petrochemicals/washington/feature-bio-jet-backers-see-us-rins-eligibility-21015154

37 www.mb.cision.com/Public/290/9900823/ba28a5848c131b4d.pdf

Using mandates to create bio-jet demand – Mandating use is a common policy approach to boost demand and develop markets for biofuels. Although Indonesia has proposed the implementation of a bio-jet mandate, a technically feasible approach based on the HEFA pathway, this might be premature and somewhat risky without certainty that supply can meet projected demand. Previously in the U.S., for example, when the Environmental Protection Agency (EPA) mandated the use of cellulosic ethanol, suppliers could not provide enough to meet the mandated demand.

One advantage that Indonesia has is the country's availability of palm and palm kernel oil as feedstock for the lower-risk and relatively mature HEFA pathway. However, the main challenge for Indonesia is that even with local feedstock the cost of producing bio-jet is currently more than double the price of producing fossil jet fuel. Thus any bio-jet mandate will have to work in combination with policies that create incentives and subsidies.

Policies that support bio-jet commercialisation – Helping investors past the "valley of death" stage of commercialising the technology will be needed, as financing for these types of pioneering projects has proven difficult to obtain, particularly at a time of low oil prices. There are several examples of such policies in the EU and the U.S., including by the U.S. Department of Defence. Airlines such as British Airways, Cathay Pacific and United Airlines have also invested in bio-jet companies.

Supply-chain policies – As well as using policies to enhance the production and use of bio-jet fuel, the entire supply chain from feedstock to bio-jet distribution needs development. Example initiatives include the EU ITAKA project and Project Solaris, which are attempts to incentivise supply-chain development. Analysis highlights the sensitivity of the MFSP to feedstock cost, so improving the efficiency of feedstock production and the development of efficient supply chains will help reduce costs throughout the process.

Industry and customers – Industry and customers can also play their part in helping expand the production and use of bio-jet fuels. For example, KLM's corporate program[38] and the Fly Green Fund[39] are some of the corporate programmes that encourage customers to cover the price premium of using bio-jet fuel.

38 www.klmtakescare.com/en/tags/biofuel-programme

39 www.flygreenfund.se/en

Conclusions

Increased use of sustainably derived bio-jet is essential for the aviation sector to meet its carbon emissions-reduction goals. Currently the vast majority of bio-jet fuels are derived from oleochemical feedstocks and use the HEFA pathway. This will likely remain the main conversion route over the next five to 10 years, as methods using biomass, lignocellulosic and algal sources, and other advanced bio-jet technologies, are still maturing. Thermochemical technologies are the most likely to provide the large volumes of advanced bio-jet required, partly because the intermediates produced by biochemical routes to bio-jet are worth considerably more in chemical, lubricant and cosmetic markets.

Although a number of commercial facilities in operation worldwide can produce HEFA bio-jet, they were primarily established to make renewable diesel. Only one facility, AltAir Fuels, is primarily dedicated to bio-jet production. Without specific interventions and incentives directed towards bio-jet production and use, current policies in jurisdictions such as the U.S. will favour the production of renewable diesel over bio-jet.

The ongoing high cost of making conventional bio-jet fuels will be problematic, as airlines unable to pay a premium for fuels that are currently two to seven times more expensive than fossil-derived jet fuels. Even if the current total global capacity for HEFA fuels of all types were to be used only for bio-jet production, supply would be less than 2% of the global aviation sector's current biofuel needs. Thermochemical based technologies using FT are considered closest to commercialisation, and construction of two facilities is expected to begin in 2016. Other efforts to commercialise similar technologies have been complicated by high capital costs and technical challenges.

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As the development of both conventional and advanced bio-jet has been slower than expected, near-term production targets, such as those set by the EU, appear unlikely to be met. The aviation sector will also face challenges in meeting its target of carbon-neutral growth by 2020. "To reach the stated carbon-neutral growth would require a stronger uptake of alternative low-carbon fuels, of which advanced biofuels currently appear to be the only option that can comply with the very specific requirements of the airline industry, including fuel quality," according to the IEA (IEA, 2015).

For 2050 carbon-emissions reduction targets require the production and use of considerable volumes of sustainably sourced bio-jet. Although several encouraging initiatives have been developed by various stakeholders there will be an ongoing need for effective policies to encourage bio-jet development and use. The international nature of aviation will likely require global coordination by policy makers, requiring the involvement of organisations such as ICAO.

Help from policy makers is required to help bio-jet along the same evolutionary path of bioethanol and biodiesel, in which a combination of technology advances and supporting policies led to the establishment of a supply chain and commercial production, even at a time of very low fossil fuel prices. Aviation's dependence on bio-jet as a primary means of reducing its carbon emissions will undoubtedly be pivotal, as "necessity is the mother of invention".

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