Aviation renewable fuels: technical status and challenges for commercialisation

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ABSTRACT

An overview of the major issues to be addressed for widespread commercial introduction and use of aviation biofuels is presented in this paper. These include the progress toward standards and approvals, bio-feedstock supply and sustainability, conversion routes to suitable fuel molecules, and policy and regulation considerations to create the necessary market and investment environment. It has been shown that while technical standards are now largely in place, biojet faces competition from biodiesel markets for feedstock, and existing sources of vegetable oil face sustainability challenges for greater supply. Other conversion routes exist that can use more sustainable feedstock, but they are capital intensive and will require a high fuel price to support investment. Policy approaches to cover the expected price premium above fossil fuel may also face political difficulties.

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This is the latest in an occasional series of survey articles by leaders in their field focusing on specific aspects of the aeronautical industry.

NOMENCLATURE

FAME	Fatty-Acid Methyl Ester, product of reaction between vegetable oil and methanol, used as a renewable road diesel.
FT-diesel	renewable road diesel made by gasification/FT technology.
FT-SPK	synthetic paraffinic kerosene, renewable jet made by gasification/FT technology.
FT	Fischer-Tropsch technology – process to convert syngas into jet or diesel.
GHG	GreenHouse Gas.
HEFA	renewable jet made from 'Hydrotreated Ester or Fatty Acid', also known as HRJ hydro-treated renewable jet.
HRJ	Hydro-treated Renewable Jet
HVO	hydrogenated vegetable oil used as renewable road diesel.
LPG	Liquid Petroleum Gas, typically C3 and C4 paraffins.
Mboe	Million barrels oil equivalent
RED	EU Renewable Energy Directive 2009/28/EC.
RFS2	US Renewable Fuel Standard.
Syngas	mixture of carbon monoxide and hydrogen made by gasification of biomass (or other carbon-based raw material) used for industrial synthesis of fuels and chemicals.

1.0 INTRODUCTION

The aviation industry is poised for significant long term growth driven by rapidly increasing commercial passenger demand and air freight in emerging economies such as the BRIC countries (Brazil, Russia, India and China). This growth will need new sources of jet fuel, as well as sustainable practices that minimise the environmental impact of meeting growing demand. On a business-as-usual basis, this tremendous growth will lead to a doubling of aviation GHG emissions. To address environmental and fuel security concerns, the aviation industry's International Air Transport Association (IATA) has set out an ambitious goal to achieve[1] two GHG reduction objectives, as shown in Fig. 1:

- Carbon Neutral Growth from 2020
- 50% reduction in GHG emissions from 2010 levels

The figure shows a breakdown of the contributory routes to meeting these targets; including use of biojet which is shown as a critical GHG reduction pathway from around 2030 onwards.

Energy security concerns are creating a strong interest in alternative fuels for the entire transport sector, and policies could be implemented focusing only on alternative fuel technology derived from fossil sources such as natural gas to liquids (GTL) However, climate concerns are creating a strong desire for fuels with a lower GHG intensity; these are typically renewable fuels from bio-based feedstocks but can also include low GHG fuels produced from non-bio sources, such as hydrocarbon waste streams. This paper focuses primarily on routes to produce fuels from renewable biomass and bio-based feedstocks. These can be converted to suitable fuels using biological, chemical and thermochemical conversion processes. All such conversion routes from these feedstocks would typically be considered to produce renewable – or bio-fuels.

Government support for alternative jet fuels is beginning to emerge in Europe and the USA. The European Commission's Directorate General for Energy ('DG Energy') together with Airbus has formed a working group of interested stakeholders (the 'Biofuels Flightpath')[2] seeking the penetration of 2 million tonnes of 'bio-jet' to be used annually in Europe by 2020. This would constitute some 5% of total EU civil jet fuel demand.

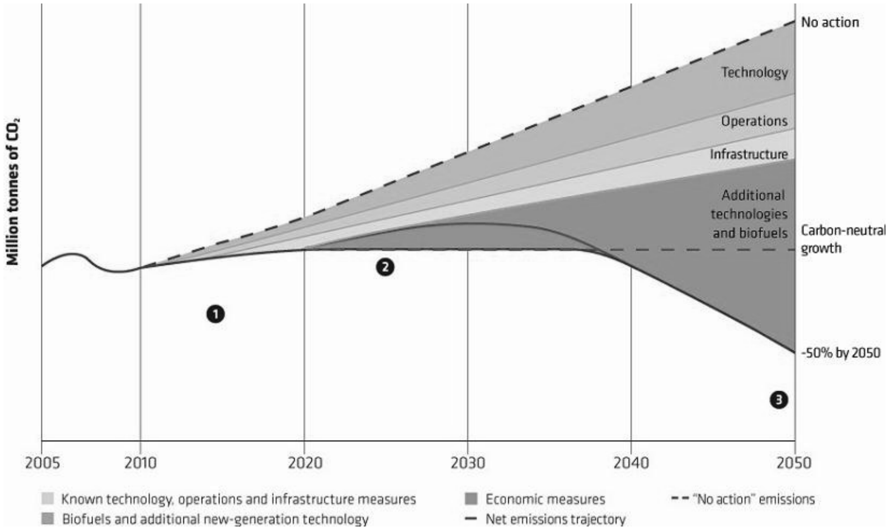

Figure 1. IATA decarbonisation targets. (Source: IATA website)

The aviation industry desires to reduce its carbon footprint and does not want to be regarded as a 'dirty' industry whose growth should be limited or made subject to draconian regulation in order to reduce its impact on the environment.

This paper reviews the overall outlook for progress toward these IATA and European goals and the more general goal of significant bio-jet usage in global aviation for the foreseeable future. This is examined in terms of progress in development of technical standards, supporting demonstrations and trials, feedstock availability and sustainability implications, conversion / manufacture processes and costs, arising policy and regulatory issues, and the investment/commercialisation outlook.

BP holds several interests in this subject: BP is a major international refiner of jet fuel and operator of hydrocarbon conversion facilities; BP is one of the world's larger suppliers of jet fuels to airlines and military organisations around the world, and BP is one of the world's largest investors in biofuels technology and manufacturing. The authors bring perspective from each of these points of view, combined with relevant external knowledge, to provide an overview of the challenges and possibilities for biojet.

2.0 TECHNICAL APPROVALS

The long haul to the future of sustainable alternative biojet begins with the basic, yet critical fuel specification demands of the aviation industry. The aviation industry requires that biojet replicates, as closely as possible, the molecular make-up of petroleum kerosene. This serves to minimise the concerns in the technical approvals and standardisation process, although it has created significant constraints on the feedstock-to-biojet conversion options, as explained later. The work on alternative jet fuel specifications (including biojet) began long before the heightened interest in renewable fuels emerged. Now, all necessary approvals for biojet use have been established and are sufficient for commercial use of biojet within the specifications.

There has been much technical work done in the last five years to establish standards and approvals for aviation biofuels. Civil aviation use of Biojet became a reality in September 2009

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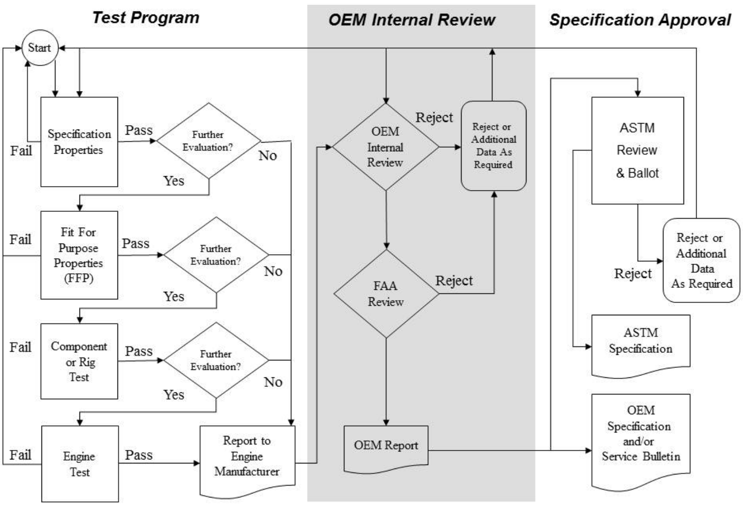

Figure 2. Overview fuel and additive approval process. (Reproduced by courtesy of ASTM)

when ASTM D7566, *Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons*[3], was first published. ASTM D7566 covers the manufacture of jet fuel consisting of conventional and synthetic material. Conventional refers to hydrocarbons derived from petroleum† and synthetic refers to hydrocarbons derived from alternative sources such as coal, natural gas, biomass and hydrogenated fats and oils. The term 'biojet' is specific to non-fossil fuel derived jet fuel containing synthesised paraffinic kerosene from the Fischer-Tropsch process (FT-SPK) or hydro-processed esters and fatty acids (HEFA) blended with conventional jet fuel certified to ASTM D1655, Standard Specification for Aviation Turbine Fuels. The detailed requirements for FT-SPK and HEFA blending components are detailed in Annex A1 and A2 of ASTM D7566 respectively.

FT-SPK and HEFA material must be blended with conventional jet fuel at quantities not to exceed 50% by volume for use in commercial aircraft. The final 'blend' must conform to the requirements of D7566 Table 1. The D7566 specification only applies at point of batch origination; therefore the 'blend' is regarded as ASTM D1655 jet fuel after certification and release into the supply and distribution system.

The other major commercial jet fuel specification, UK Defence Standard 91-91, approves Biojet by reference to ASTM D7566 in Annex D, Additional Requirements Applicable to Fuels Containing Synthetic Components. FT-SPK and HEFA material meeting the requirements of D7566 Annex A1 or A2 may be used, either individually or in combination, as blending components in jet fuel meeting the requirements of Defence Standard 91-91 up to a total combined 50% synthetic component by volume.

The numerous applications for approval and requests for guidance on the process to assess new fuels and additives for commercial use led to the complete rewrite of ASTM D4054, Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives[4]. This standard practice was originally published in 1981, long before alternative fuels were of much interest to the civil aviation industry. ASTM D4054 now provides clarity on the approval process to give a prospective applicant a better understanding of the testing required, identification of key stakeholders and decision gates and insight into the cost and volumes of material needed to complete the process.

† Sources including crude oil, natural gas liquid condensates, heavy oil, shale oil and oil sands.

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In general, the approval process has three parts as shown in Fig. 2; the test program, the original equipment manufacturer (OEM) internal review and balloting by ASTM to review, approve and promulgate the new specification. For biojet, the 'new specification' means adding a separate annex to ASTM D7566 to define the detailed batch requirements for the new synthetic blending component. A number of novel pathways are under development via catalysis and synthetic biology to produce biojet. Regulatory approval is automatically granted once the new annex is incorporated into D7566, allowing use in all commercial aircraft which utilise the specification.

3.0 TECHNICAL AND OPERATIONAL VALUE OF AIRLINE TRIALS

Civil airlines and the military have conducted a large number of flight trials in support of Biojet development. One of the key early trials was carried out in February 2008 by Virgin Atlantic, where one GE engine of a Boeing 747 was operated on a blend of 20% FAME derived from Babassu Palm Oil/Coconut Oil with 80% conventional jet fuel, for a flight from Heathrow to Amsterdam. The biofuel mixture was supplied by Imperium Renewables and the flight was strictly experimental as no formal approval for the specification and use of Biojet had been developed at the time (i.e. prior to the publication of ASTM D7566). The trial received widespread publicity and surely inspired further trials by other airlines, and created a great deal of debate.

After this initial venture into flight testing, Industry work to formally progress the development and approval of biojet has accelerated, the target being a 'drop in' fuel product for airline / military use. Various supporting demonstration flights have been performed, for example by Air New Zealand, KLM, Finnair, Iberia, United Airlines and Thomson Airways with product becoming the now more familiar fully hydrocarbon HEFA blend manufactured from a variety of feedstocks such as jatropha, camelina, algae and animal fats. An extensive six month trial has recently been completed by Lufthansa between Hamburg and Frankfurt. Strict guidelines were followed and only product meeting ASTM D7566 was acceptable, in this case a blend of 48·6% *v/v* biojet manufactured by Neste Porvoo refinery in Finland and 51·4% conventional jet fuel. The trial, reported at the Aviation Fuels Committee meeting in London in February 2012, offered an opportunity to evaluate the practicalities and performance of using biojet on a long-term basis. An Airbus A321 was used on the route and a consortium of 12 Universities/Industry members was involved. Fuel quality was closely monitored from tankage, through the distribution system and into aircraft and extensive analytical tests evaluated in-service engine operation, fuel consumption and pre/post trial hardware performance. Over 1,000 flights were performed using 1,557 tonnes of biojet blend which delivered seamless and reliable operations expected in aviation.

While civil airline trials have received much publicity, the military, as operators of many variants of fixed and rotary wing aircraft at the limits of the performance envelope, must be recognised for its contribution to the evaluation and eventual approval of biojet. Over 1·5 million gallons of alternative jet fuel has been purchased by the US military and numerous lab tests, rig scale, ground and flight tests undertaken in recent years. A broad range of test platforms has been utilised, ranging from the C-17 transporter to the F-22 Raptor to ensure product is fit-for-purpose. These tests and accumulated expertise have been a great benefit to the civil programme. The military have also been watchful of the sustainability issue, as illustrated in the USA where its purchase of biojet must be environmentally compliant with Section 526 of the Energy Independence and Security Act.

Airline and military trials have confirmed the suitability of the technical approvals and revised standards, and have established confidence that greater use of biojet will not cause operational or safety concerns. They have also served to fuel the debate and consideration of biojet to offset environmental effects of aviation. With testing, standards and fuel specifications completed the industry can now confront the biggest challenge to biojet – commercial viability.

4.0 FEEDSTOCK AVAILABILITY AND SUSTAINABILITY

The future viability of biofuels and the societal and economic case for producing them will depend on the availability of suitable feedstock and the degree to which this feedstock can be produced sustainably. Much work is being done in the US and in Europe developing biological or chemical conversion routes to enable a wider range of feedstocks that can be used for biofuels. While these conversion technologies are discussed in Section 6.0, this section focuses on feedstocks that have potential for conversion to bio-jet fuel.

Significant biomass feedstocks include:

- Oils – primarily vegetable oils and animals fats (including waste oils), and potentially microbial oils and algal oils;
- Lignocellulosics – wood, energy grasses and agricultural residues;
- Starches and sugars – simple carbohydrates produced directly in crops such as sugar cane & sugar beet or by hydrolysis of complex carbohydrates such as starches found in cereals.

Researchers have found routes to make fuel from all of these sources but the economic viability, sustainability and scalability of biofuels routes are heavily dependent on the availability and productivity (i.e., agricultural yield) of feedstocks. Here we describe the main feedstock types, their current and potential future supply and sustainability characteristics.

4.1 Oils

Current feedstocks for the HVO / HEFA route are vegetable oils and waste oils. Vegetable oils, such as rapeseed, palm, soy, sunflower, are commonly used to make biodiesel or HVO as a road transport fuel. However, aviation biofuel trials using oils have predominantly focussed on non-food oil crops such as camelina and jatropha, oils extracted from algae, or waste oils such as used cooking oil (UCO) and tallow. The industry is keen to avoid real or perceived negative impacts including competition with land for food production, competition for water, and negative impacts on biodiversity (see ATAG 2012, SAFUG, 2012).[5,6] In practice, sustainability impacts need to be identified and avoided for any biofuel crop, edible or not, and will depend heavily on land types and crop management practices. For example, the US EPA has determined that in the near term camelina is most likely to be grown in rotation with wheat in the US, in a period when the land would otherwise be left fallow, and so should not lead to competition for land. However, it could be grown elsewhere, or in the longer term, on land that would otherwise be used for food (EPA, 2012)[7].

The availability of vegetable oils for aviation biofuels is likely to be constrained by global vegetable oil supplies, as well as increasing demand from food, feed, industrial and road transport fuel markets, driven by rising population and incomes, and by biofuels mandates. The total global supply of the four main vegetable oils was 124Mt in 2010, of which 14Mt was used to produce road transport fuels, Fig. 3 (Source: LMC International)[8]. Projections for 2020 show supply reaching only 197Mt, compared with a total demand of 213Mt of food, feed and industrial demand, plus global biodiesel demand (including that requirement set out in EU National Action

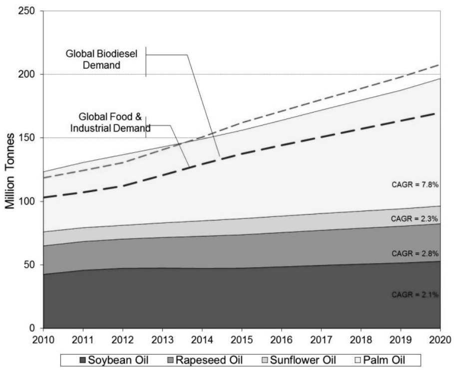

Figure 3. Outlook for vegetable oil supply. (MTe/year) (Source LMC International)[8]

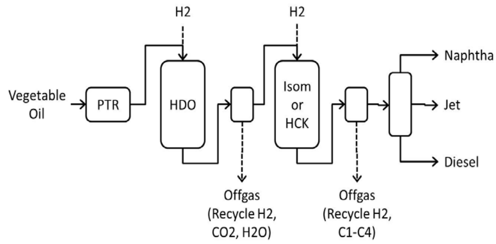

Figure 4. Schematic of representative HVO Plant.

Plans). In addition to this shortfall, the majority of the growth in supply is made up of palm oil, where some production appears to come from recently deforested areas, and therefore may not meet sustainability requirements of EU biofuels policies. Although there is some scope for technology and innovation to improve vegetable and palm oil yields, it remains to be seen whether any such advancements can significantly offset price pressures caused by the large increase in demand. Consequently, expectations are that vegetable oil will trade at a high premium for the foreseeable future, thus creating an economic challenge for biojet (see below).

New types of vegetable oils, such as camelina and jatropha, will add to this overall supply picture. Whilst the suitability of land for their cultivation is relatively large, current production of these crops is small and will require considerable ramp up to reach significant volumes, together with further assessment of their sustainability (E4tech, 2009)[9]. Similarly, algae could be grown using non-productive land, avoiding competition with food, but are at an early stage of development, with considerable technical improvement and cost reduction needed for commercialisation. Although production costs of these non-edible oils should decline and may mitigate pressure on food prices, competition from the industrial sector (e.g. in power and heat production) and from road transport biofuels may shift supply away from the aviation fuel sector.

Moreover, recent work by the Energy Biosciences Institute at UC Berkeley[10] has shown that there is likely to be a floor to the production costs for algal oils, significantly above current vegetable oil prices, likely giving a range of \$240 – \$400/barrel (oil equivalent) for a finished biodiesel fuel component. Therefore, absent a major technology breakthrough, the prospects for biojet from algae are challenging.

4.2 Waste oils and tallow as feedstock for HRJ/HEFA

The regulatory incentive in Europe for road transport fuels made from wastes and non-food feedstocks has since 2010 caused significant quantities of used cooking oil (UCO) and tallow (animal fats from meat rendering facilities) to be converted to biodiesel. Fuels made from these feedstocks qualify for ‘Double Counting’ for compliance with national renewables mandates under the EU Renewable Energy Directive 2009/28/EC, or RED[11]. The high value of such biodiesel for compliance purposes has caused an increase in commercial activity in collecting used oil, and bringing it to Europe for conversion to biodiesel. This has caused concerns that the incentive encourages abuse, by encouraging ‘waste’.

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Some airline trials have also made use of UCO or tallow, processed to HRJ. While responsible sourcing of this is generally considered sustainable, naturally there are limited volumes available. Currently it is believed that most biofuel from UCO ends up in road transport and this sector could utilise much more than consumed today. However there are already concerns from some national regulators over the definition of waste as it applies to UCO, the quantities available, and abuse of the category through false categorisation of new oils as waste. Attempts to access UCO feedstock beyond current supplies, either for biodiesel or biojet, runs the risk of creating 'waste' from unused feedstock in order to capture the benefit of double counting under the RED. It is reasonable to expect that policy treatment of UCO will eventually enforce robust justification of genuine waste sources and that such action will limit the availability of UCO. In such a situation, use of UCO to make biojet will detract from today's biodiesel production and simply require 'backfilling' with likely new vegetable oil for producing biodiesel.

4.3 Lignocellulosic feedstocks

Lignocellulosic feedstocks are 'woody' materials including energy crops, agricultural residues, forestry material, and wastes. Energy crops are woody or grassy crops grown specifically for energy, such as miscanthus, switchgrass and short rotation coppice willow. Interest in these crops is driven by the potential for high yields with low agricultural inputs, on poorer quality land than needed for food crops (IPCC, 2011)[12]. Agricultural residues, such as straw, and forestry residues offer low cost, but more dispersed sources of feedstock, with low GHG emissions. Similarly, using the organic fraction of municipal solid waste, could offer emissions reduction compared with landfilling, and potentially receive a gate fee for disposal.

There has been a wide range of studies over the last 20 years on the potential global biomass resource (UKERC, 2011)[13], mostly from lignocellulosic feedstocks. They aim to estimate what the resource for bioenergy uses will be out to 2050, considering the availability of energy crops, agricultural residues, forestry material and wastes, and subtracting resources required for other uses. Studies vary considerably on factors such as food demand, diet and yields of food and energy crop yields, and give very wide ranging results, from zero to more than twice current global primary energy consumption. However, a review of these studies by UKERC (2011) concluded that achieving the first 100 exajoules (EJ) of biomass production sustainably is the best approach for policy. About 70EJ of this would be from energy crops, 30EJ from wastes and residues. This is equivalent to a fifth of current global primary energy supply, or 5·5bn dry tonnes biomass, or if all converted to biofuel around 20–25mboe/d – equivalent to around 60% of current global road transport fuel demand. A similar review by the IPCC (2011) estimated that 100-300EJ/year by 2050 could be achievable, or up to 75mboe/d. There will be competition for use of these feedstocks from heat, power, road transport fuel, and chemicals sectors, depending on the location and feedstock type.

Clearly such large numbers suggest great potential for use of lignocellulosic biomass for production of biofuels. However, there remain challenges to ramping up supply of these feedstocks, through planting crops or gathering highly dispersed residues, and to converting them into highly specified biofuels. These challenges are addressed in a later section, and the degree to which these challenges can be addressed also has a bearing on how biofuels (including biojet) use may compete with other potential uses outlined above.

4.4 Sugar and starch crops

Sugar to diesel and alcohol to jet routes could use sugar and starch feedstocks that are currently used to make ethanol for road transport, such as sugarcane, sugarbeet, corn and wheat. Growth of these crops for fuel is a mature sector, with sugar cane to ethanol for fuel in large scale commercial production in Brazil since the 1970s. The degree to which these edible feedstocks will be acceptable to the aviation sector is not yet known. However, as discussed above, the sustainability of each crop will vary, depending on the land and management practices used, and may be better than a non-edible option in some cases. Sugarcane, for example, is a perennial crop with high yields, and so low land use, which can be used to produce sugar and fuels together.

5.0 SUSTAINABILITY CERTIFICATION

As discussed above, airlines and other stakeholders in the aviation biofuels sector are keen to ensure that the fuels they use are sustainable. For all biofuels, sustainability can be established via regulatory requirements or voluntary certification schemes, which generally cover GHG impacts of their production, environmental criteria such as impacts on biodiversity, soil, water and the air, and social principles, such as working conditions, and land rights.

USA and EU biofuels policy includes sustainability requirements as a condition of support. Under the EU RED[10], biofuels supported by policy, or used to count towards Member State targets, must meet minimum thresholds of 35% GHG saving compared with fossil fuels, increasing to 50% in 2017 for existing plants, and 60% for new plants. In addition, they must not be produced on land that is highly biodiverse, or that has high carbon stock, such as forests. This will apply to aviation biofuels if supported by policy or if used to gain EU ETS exemption (EurActiv, 2012)[14]. This refers to use of biofuels to reduce the obligation to surrender EU ETS allowances, thereby reducing compliance costs. Proof that these criteria are met is through sustainability certification schemes that are checked by Member States or approved by the European Commission, with seven schemes currently approved (EC, 2012)[15]. In the US, the Renewable Fuel Standard, RFS2 (EPA, 2010)[16] also sets sustainability standards and GHG savings minima.

Aside from the regulatory requirement, most aviation biofuels projects are working to achieve certification of their fuels to voluntary schemes. In particular, many are working with the Roundtable on Sustainable Biofuels (RSB) certification system, one of the EU approved schemes.

With regard to the overall picture of availability of sustainable feedstock for biojet production, it can be seen that many sources are being developed, there is a good understanding of their availability, and that the right steps are being taken to ensure that they are certifiably sustainable. However feedstocks for biojet are essentially the same as those for biodiesel, and those feedstocks that suit the available conversion technologies are likely to have some restrictions to the supply for the foreseeable future. Therefore the two demands for biodiesel and biojet will compete for these feedstocks.

6.0 TECHNOLOGY ROUTES AND COMMERCIALISATION PROSPECTS

Fuel technology pathways currently exist to convert sustainable biomass feedstocks into biojet fuel that meet the rigorous standards demanded by the aviation sector. The remaining challenge is to drive down production costs and to overcome the incentives to produce road biofuels to enable

Table 1
Commercial renewable diesel facilities

Process	Location	Commissioned	HVO Production kTe/year
Neste-1	Porvoo, Finland	2007	170
Neste-2	Porvoo, Finland	2009	170
Neste	Singapore	2010	800
Neste	Rotterdam	2011	800
Dynamic Fuels	Giesmar, Louisiana, USA	2011	200
Darling/Valero	Norco, Louisiana, USA	2012?	400

(Source: Neste, Dynamic Fuels & Darling press releases)

Table 2
Material balances for 'Max Diesel' and 'Max Jet' versions of vegetable oil hydrogenation

Mass, kg	Max-Diesel operation	Max-Jet Operation
Veg Oil	–100	–100
H_2	–2·7	–4·0
H_2O	8·7	8·7
CO_2	5·5	5·4
C3	4·2	4·2
C4	1·6	6·0
C5+ Naphtha	1·8	7·0
Jet	0·0	49·4
Diesel	80·9	23·3

(After Pearlson, MIT)

biojet to flourish. Given the state of current technology and the incentives to produce biodiesel or HVO, it is difficult to see biojet making significant inroads into the market.

Conventional renewable road fuels are mainly oxygenates (fuel molecules containing oxygen in the molecular structure) such as fatty-acid methyl esters (FAME) and ethanol. There are technical limitations on the amounts of these components which can be used in the majority of road vehicles which has led to the development of advanced renewable fuels such as hydrogenated vegetable oil (HVO) or wood-derived FT-diesel. The manufacturing technologies for the conversion of biomass into renewable jet closely resemble those for advanced renewable road diesel and will draw on the same feedstocks. However, differences in production processes between HVO and HRJ and the market prices for HVO road fuel may encourage production of HVO rather than HRJ.

6.1 HVO and HRJ/ HEFA

Figure 4 shows a representative block diagram for the HVO diesel process. The vegetable oil first has to be purified to remove impurities such as calcium, sodium and phosphorus, and is then catalytically deoxygenated using hydrogen. For feed stocks such as soybean, palm or rapeseed oils, and animal fats, the raw HVO product typically comprises linear C15-C18 paraffins which have would lead to poor low-temperature properties in the finished diesel or jet. The raw HVO is thus hydroisomerised to introduce branching plus some reduction of chain length by hydrocracking. The de-oxygenation reaction is very selective – each ton of vegetable oil typically yields ~800kg of diesel-range paraffins, but the hydroisomerisation/cracking step downgrades some of the diesel to naphtha and LPG (where these two components have a significantly lower value). The yield loss depends on the severity required.

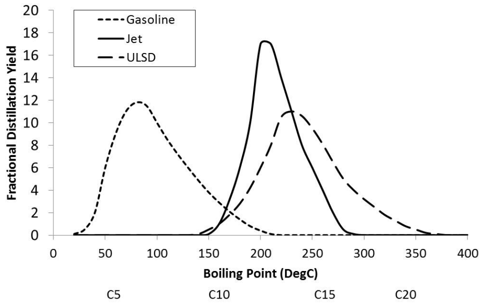

Figure 5. Representative boiling ranges of fossil gasoline, jet and diesel.

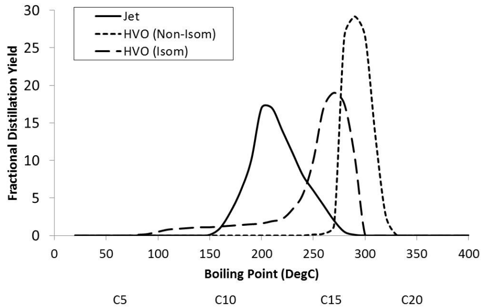

Figure 6. Representative boiling ranges of conventional jet, un-isomerised and isomerised hydrogenated vegetable oil.

HVO for renewable diesel has been commercialised with global production capacity currently ~2·5 Million Tonnes/year; individual plants capacities vary from 170 to 800kTe/year (Table 1). Production costs for HVO diesel can be estimated with reasonable confidence:

- Capital Investment – Reported investment costs for actual projects are in the range of $0·9 million to 1·2 million per kTe/year of HVO production[17-24] with detailed cost breakdowns in more academic work.[25, 26]
- Feedstock – Vegetable oil is relatively expensive with 2011 prices for soybean-oil (Chicago Board of Trade) and palm oil (Kuala Lumpur Exchange) trading in the range $1,350-1,450/Tonne and USD1,000-1,200/Tonne respectively. Over the same period, 'finished' jet and diesel prices were in the range USD950-1,100/Tonne (Platts; Rotterdam FOB.)
- Operating cost – This includes energy & process chemicals such as catalysts as well as the non-process costs such as staff, insurance, maintenance, local taxes. However, the biggest operating cost is hydrogen. An HVO plant[27,28] consumes ca 30-50kg of H_2 per Tonne of veg-oil, which is several times higher than typical oil refinery processes.
- By-product credits – An HVO plant also makes methane, propane, butane and naphtha (C5-C8) in addition to jet or diesel. These are unavoidable consequences of the molecular structure of the vegetable oil. Depending on local markets one may be able to sell these as 'green' feedstocks or energy but this is not a foregone conclusion.

Based on the capex and opex figures above plus assumptions of 20-year depreciation, 7% return on investment and naphtha sales at typical chemical naphtha prices, we estimate that palm-based HVO diesel can be produced for $1,500-1,700 per Tonne. Note that feedstock costs constitute at least 80% of the total production cost.

At this point, it is important to compare the properties of road diesel and jet; although both are described as 'distillate fuels', their different boiling ranges have implications for the relative cost of producing renewable jet and renewable diesel. Figure 5 shows that jet has a narrower boiling distribution that diesel, and contains little material boiling above 270°C. The Jet-A1 specification (D1655-04) for example does not allow any material boiling above 300°C, whereas the European diesel specification (EN590-2009) permits 5vol% to boil above 360°C. ASTM D7566 for HRJ does not allow any material boiling above 300°C + imposes a freezing point limit of –40°C.

The most common feedstocks (palm, soy, rapeseed and tallow) initially yield C15-C18 n-paraffins which boil in the range 270-320°C. To meet the D7566 specification requires severe isomerisation plus some cracking of the paraffins which will shift the distribution to lower boiling

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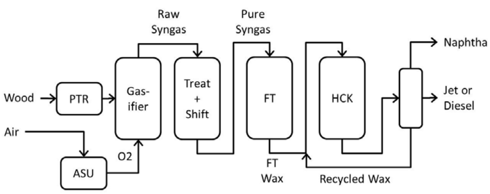

Figure 7. Schematic of representative FT-diesel plant.

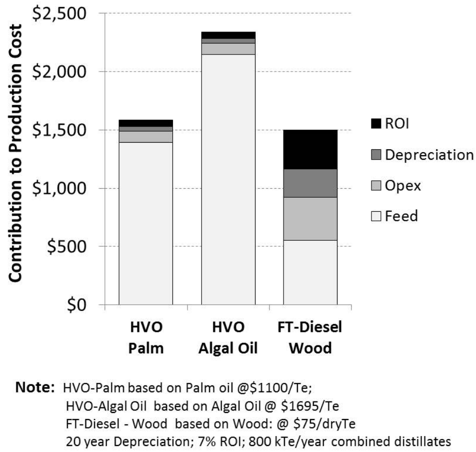

Figure 8. Production cost structures of hydrogenated vegetable oil, hydrogenated algal oil and FT-diesel.

range but also makes some lighter paraffins in the LPG and naphtha range. Even so, distillation may be required to remove components boiling over 300°C. Figure 6[28] shows some representative boiling ranges of conventional jet, un-isomerised HVO (C15-C18) and isomerised HVO which has been 'stabilised' by removal of LPG. The consequence is that increasing the isomerisation severity to make more jet reduces the yield of renewable distillate and increases the yield of LPG and naphtha. There is little published data to quantify this, but an estimate by MIT[27] suggests that shifting a 'max diesel' HVO operation to make a 60:40 jet to diesel product slate would reduce the distillate yield by ~5%. MIT also note that hydrogen consumption and capital costs increase; additional fractionation will be needed to manage the jet quality as well as extra infrastructure to handle the additional product stream.

In principle, one could push all the way to a 'jet-only' product slate but this would entail even greater losses to naphtha and LPG. We are not aware of a 'jet-only' facility; as yet, the main supplier of renewable jet for airline trials has been UOP via its 200bbl/day (8kTe/year) HVO/HEFA demonstration plant in North America[23]. In summary, it has been shown the added complexity and lower yields for biojet HVO would likely cause this to have a higher cost compared to biodiesel HVO.

6.2 FT-Diesel and FT-SPK

Figure 7 shows a block diagram for a representative FT-Diesel Technology. Wood (or similar lignocellulosic material) is crushed then gasified using high-temperature steam/oxygen to make syngas. After purification, the syngas is converted using catalytic Fischer-Tropsch (FT) technology to make a high-boiling paraffin wax. This is catalytically hydrocracked to make paraffinic diesel, jet and naphtha. Heavy products (such as partially converted wax) are recycled back to the hydrocracker (although some markets may find uses for industrial fluids such as lubricants.) Note that hydrocrackers also isomerise the hydrocarbons, thus cold-flow properties are unlikely to be an issue.

FT technology is commercially established for production of diesel from coal or natural gas, but the biomass version has not yet been deployed at commercial scale. There are no operating wood-based FT-Diesel plants, but several commercial projects are under consideration. A large (world-scale) FT-Diesel plant would yield ~600kTe/year of liquid products & consume ~4MTe/year of wood (dry-basis), roughly equivalent to a world-scale pulp/paper mill.

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- Capital Investment – BP estimates that the capital cost of a FT-Diesel facility is between \$5million and \$7million per kTe/year depending on scale[29,30,31].
- Feedstock – Wood is rarely traded and a local supply chain might well be required. Depending in the distance it has to be moved, the price might trade in the range \$50 to \$90 per dry Tonne.
- Operating cost and By-product Credits – As with HVO, the non-process costs include staff and maintenance, but this is a more complex facility operating under more extreme conditions. Process costs include things like catalysts, but unlike HVO there is no need to import hydrogen. The FT-Diesel by-products could include power as well as naphtha.

The production cost is estimated at \$1,500-1,800 per Tonne of liquid products, but unlike HVO the cost structure is dominated by capital & operating costs.

The majority of FT-Diesel designs are intended for road diesel production but the nature of the hydrocracking step would allow optimisation for jet. As with HVO, this would entail some loss of distillate yield in favour of naphtha e.g. an 80:20 ratio for diesel to naphtha would translate to something like a 60:40 jet to naphtha ratio. The impact on the renewable jet price would reflect the price obtained for the naphtha; this is generally lower than the price of diesel meaning that the price of FT-SPK would have to be higher than the price of FT-Diesel in order to make the same financial return.

6.3 Technology commercialisation outlook

The technology to make renewable jet from vegetable oils or wood exists today, but is in the very early stage of commercial implementation. Wood-derived FT-Diesel has not yet been commercialised, but similar technology has been used commercially for gas- or coal-based production. In both cases, development has focused on production of renewable road diesel, but in principle both can be adapted quite readily to make renewable jet. In both cases, shifting from diesel to jet will entail a loss of distillate yield with resulting production of 'green' naphtha which currently is less valuable than renewable diesel.

The different cost structures (Fig 8) imply that future developments will be influenced by different factors. The viability of HVO/HEFA will be set by vegetable oil price (or availability of alternatives such as algal oils.), with very little potential for cost reduction in the conversion plant. Conversely, the price of FT-diesel or FT-SPK is much more influenced by the capital cost of the facility. Improvements in technology might occur in time, but are unlikely to lead to a major reduction in cost.

The analysis presented in this paper shows a consistently higher cost of biodiesel and biojet over both fossil diesel and fossil jet fuels. This is shown in Fig. 8 for typical market pricing at the time of preparation of this paper (mid 2012). This price cost premium has held throughout the relatively short history of biodiesel and biojet fuel. This premium may be significantly reduced if the cost of crude rose dramatically relative to biofuel feedstock costs, but this is unlikely given that all commodities tend to respond to the same inflationary pressures. A full discussion of commodity price correlations is outside of the scope of this paper. However the authors believe that market price linkages are already established (especially for vegetable oils for HVO/HRJ) and that dislocation sufficient to significantly reduce or eliminate the 'bio premium' is unlikely for the foreseeable future. Due to the continued outlook for high capital and logistics costs associated with aggregating and converting lower density feedstocks, it is unlikely that significant price reductions for non-vegetable oil feedstocks will materialise.

Other technologies for renewable jet and diesel are being investigated[32-43]. Examples include biochemical or thermochemical conversion of sugars to jet precursors, pyrolysis of wood or conversion of biobutanol. In principle, these approaches would help utilise raw materials which have greater availability and less sustainability risk than vegetable oils (e.g. sugar cane, lignocellulosics) but these same raw materials will be in demand for road fuels (and food in the case of sugar cane.). In addition, some of the new products also have alternative uses other than jet e.g. speciality chemicals, lubricants or road fuels. Therefore, even with these new technologies, renewable jet will still have to compete with other markets both for raw materials and for products. As yet, none has been demonstrated beyond pilot scale as regards jet production (although some are in the early stages of commercialisation for speciality chemicals). It will be interesting to see if any of these technologies will have significant renewable jet production before 2020.

Vertical integration of the fuel supply chain leading to deeper and long term integration with upstream biofuel and bio-feedstock production may provide the aviation sector with some price hedge against peak prices in fossil fuel and biofuel markets. There are now several examples of collaboration between fuel purchasers and manufacturers and the success of these ventures remains to be seen. However, vertical integration and use of long term contractual arrangements cannot overcome the fundamental cost issues identified in this paper. Biojet production beyond vegetable-oil based road fuels, remains commercially ambitious and unproven at scale – changes to market structure alone will not alter this fact.

7.0 POLICY AND REGULATORY OUTLOOK AND MARKET DEVELOPMENT

Policy and regulations to encourage biofuels use in road transport have been in place in the USA, Europe, Brazil and elsewhere for over decade in many cases, and this has resulted in a variety of agricultural, conversion industry, infrastructure and market developments to facilitate the production and usage of these fuels. Lessons learned are highly relevant to consideration of how further use of aviation biofuels might be achieved by policy or regulatory approaches.

The most relevant experience comes from the regulation and use of biodiesel in Europe, as a result of the chemical similarities between diesel and jet fuels, and the similar feedstocks and processes that can produce biodiesel and biojet.

There are three main policy aspects discussed here:

1. Making biofuel economic for fuel supply chain
2. Feedstock competition
3. Cost of carbon issues

7.1 Making biofuel economic for supply chain

As we have seen biodiesel is produced at scale today, supported by numerous policy measures. Today, the vast majority of biodiesel is made from vegetable oil, (mostly new, small quantity of UCO), with a small percentage from tallow. The percentage from other feedstocks and conversion routes (such as FT-Diesel) is estimated to be much less than 1% of global production. This reflects the relative ease and lower costs of the vegetable oil routes, compared to other routes. However, biodiesel today still has a (market, commoditised) cost around 1·4 × cost of petroleum diesel. For a policy or regulation to be successful, it must create a market where such a price can be passed on or otherwise recovered by fuel suppliers, and for investors in manufacturing plant, this needs to be robust and stable over a timeframe sufficient to recover investment costs and also make a profit. In the relatively short history of biofuels regulation, three methods have emerged to achieve this:

7.11 Tax/duty relief

Where fuel is supplied to end users taxed, as with most road transport fuel, the bio-component has been subject to a reduced or zero rate of tax. This typically has made the biofuel cost-competitive with the petroleum fuel. As the majority of aviation fuel is supplied untaxed this is not a viable option for biojet.

7.1.2 Mandated volume

Here, a fuel supplier simply cannot supply fuel to customers unless qualifying biofuel is blended at a suitable percentage level, or in some cases a penalty is paid. Some markets now have a tradable compliance ticket system – examples include the Renewable Fuel Standard (RFS)[7] in the USA and several national schemes in Europe such as the UK RTFO[44]. A mandate has an immediate effect of forcing the fuel suppliers to pay the necessary price to obtain the biofuel for blending, and this is then typically fully recovered in the price to final customers. For biojet this would be expected to work in exactly the same way; the customer that buys from the mandated market would pick up the additional cost of the biofuel.

Experience with this approach has been limited to road transport within national borders where fuel price impacts cause only limited competition issues (such as with cross-border freight transport). However for international aviation, a mandated approach, with the consequential fuel price impact may bring competition problems unless global implementation was possible or other means to mitigate fuel price competition concerns.

There are several possible approaches for mandating biojet use in aviation, not limited to the following:

- Aviation fuel supplier obligated to supply a quantity or proportion of biojet across nation state or regulatory region, over a given period of time.
- Airport places obligation on fuel suppliers or airlines to supply/use quantity or percentage of bio-jet for all flights from that airport
- Airline obligated regionally or globally to use quantity or percentage of bio-jet for all operations.

Each of these options would have merits, but would also likely face implementation challenges due to the competitive global structure of the airline sector and the jet fuel industry. In addition, the technology and market challenges in producing biojet relative to the incentive to produce road fuel would raise the very real prospect of having no investment in biojet supply capacity. A full analysis of these options is beyond the scope of this paper.

7.1.3 Compliance with mandate in one sector through supply and cross-subsidy in another.

This scheme is a potential variant of the above 'mandated volume' method. Here, biojet supplied to airline, could qualify for compliance with a (likely national) road transport biofuel mandate. Typically the biojet use would generate compliance tickets, which could then be sold

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on the road transport mandate ticket market, to mandated road transport fuel suppliers. Here, the cost of these tickets would effectively borne by road transport fuel customers. The ticket price would likely be set by the value of biodiesel tickets, and this may (or more likely may not) fully cover the additional cost of biojet over petroleum jet. This scheme has been proposed by some aviation stakeholders, and does appear to set up a mechanism to cover at least some of the cost premium for biojet. However, currently where this approach is technically possible, it is observed that the full increment of the biojet price over petroleum jet is not covered, leaving one party to incur an additional cost. Also there is a wider policy question that arises. Whether this solution is acceptable at scale is essentially a political one: such a construct is effectively a subsidy for biojet use in airlines, paid by road transport fuel customers. This paper makes no attempt to judge whether this solution is fair for aviation or road transport industries, or their respective customers. Many stakeholders in aviation argue that such an approach (or another approach that involves an incentive paid by other parties) is appropriate given that aviation has few other decarbonisation options compared with road transport. Judgement of such issues is for government and politicians. Currently, given the political sensitivities over road fuel costs in the US and Europe, politicians may be reluctant to endorse such an approach beyond low levels of biojet use.

As is evident from the brief analysis here, each policy approach has inherent problems, and none appear to give a clear route to provide robust, sufficient support, at scale, likely to politically acceptable for a long period of time.

7.2 Feedstock competition and cost of carbon issues

For the foreseeable future, there will be limits to the usable, economic feedstock supply, compatible with available conversion technologies and conversion industries, for production of biodiesel and biojet. Not all sectors may be able to access the preferred feedstocks in the quantities desired. Societal choices may need to be made to effectively direct feedstocks to certain sector, or alternatively, biofuels and feedstock markets may make these choices for us. Currently, some aviation industry representatives suggest that aviation should be given preferential access to biofuels feedstocks on the grounds that aviation has few other carbon mitigation options (such as electricity/batteries, or hydrogen power, in the near or medium term at least. However there are counter arguments to this:

1. Use of feedstock for conversion to aviation biofuels may have a lower overall efficiency/yield than turning into biodiesel, biogasoline, or for that matter, burnt in power stations to produce electricity; it would make more sense for the environment to use feedstock for these other purposes;
2. It is far from clear how such prioritisation would be achieved. It may require restriction on farmers or feedstock market regulation, which may disincentivise growers to choose to produce the feedstocks unless they can expect a competitive price; and
3. Without any regulated prioritisation, biojet feedstock buyers would simply have to compete with other feedstock buyers (including for biodiesel). Interfering with such markets whether nationally or internationally would be fraught with difficulties.

Far more analysis is required to evaluate potential policy choices. But the tightly constrained jet specification (compared with for example, the more flexible specifications for biodiesel, or use of biomass for power), will likely make conversion efficiency lower, GHG intensity higher, and costs higher. Certainly this is true today of the only route available at scale today for biojet, HRJ compared with HVO diesel. If this turns out to be true for other routes then it could be argued that better value for society and the environment will be achieved by use of the feedstock/biomass elsewhere than for bio-jet production.

7.3 Cost of carbon considerations

It is also important to understand the cost of carbon mitigation achieved by use of biofuels. The effective carbon cost can be derived relatively simply:

- A tonne of petroleum jet fuel, when burnt, will release approximately three tonnes of CO_2.
- If we were to take the carbon intensity of the biojet, for example at 50% that of petroleum jet, then the tonne of biofuel would save 1·5 tonnes CO_2
- If the biojet were to cost a premium of $600/Tonne over fossil jet (a figure that today may be optimistically low) then the carbon cost would be 600/1·5 or $400 per tonne CO_2.

This $400/tonne figure is indicative and is likely to be on the low side because either a) biojet will cost more, or b) the carbon intensity may not be as good, or indeed both. Note that the currently available market cost for mitigating carbon, at large scale, in the industrial and power sectors, as given by the cost of EU ETS permits, is less than €10/Tonne CO_2.

The $400/Tonne in the above example is indicative and is based on a significant price differential – the premium of biojet over fossil jet fuel. If the price differential narrowed (higher crude oil prices, lower biojet prices, or both) the implied carbon price would be reduced. The outlook for such a premium is discussed in Section 6.3. The authors of the paper believe it is unlikely that the premium will be significantly reduced in the foreseeable future.

The comparisons with the current EU ETS permit price and views for the future outlook also deserves explanation. Although detailed market analysis of future ETS prices was not conducted, the authors think that the drivers for the current low ETS price (e.g., slow economic growth) will likely persist for the medium term. Therefore, the tightening of the carbon cap in the next phase of the ETS would not increase carbon prices significantly above the 7 – 10 Euro per tonne price today. It seems highly unlikely that the current carbon price will increase over 30 fold to come close to the implied $400 tone cost of abatement today. On this basis, the authors believe that biojet is likely to continue to be a very expensive form of carbon mitigation relative to the market price of carbon available in the ETS. Nevertheless, the authors acknowledge that possible future scenarios exist for the convergence of biojet implied carbon price and cap-and-trade scheme carbon prices.

Given the likely supply difficulties and high costs (and carbon abatement costs) associated with biofuels for aviation, it is the author's considered view that, for the foreseeable future, it will make more economic and environmental sense for aviation to pay other sectors to make GHG emission reductions 'on their behalf'. This could be achieved by a 'cap and trade' scheme (of which the EU ETS is an example) or other flexible mechanism to promote a market based carbon price, and this would also promote adoption of improved aviation efficiency and other operating efficiencies that will reduce GHG emissions.

8.0 CONCLUSIONS

Up to 2020

- The major technical approvals and supporting trials necessary to prove the operational suitability of biojet in blends with petroleum jet have been successfully delivered.

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- Outlook for supply of sustainable vegetable oil based biojet is limited and any significant demand will exacerbate existing concerns arising from the sourcing of vegetable oils for biodiesel, for compliance with road transport biofuel mandates.
- Regulatory structures already create strong incentives for biodiesel, resulting in a clear commoditised market price premium over petroleum diesel. This is not the case for biojet, and this hampers any potential investment in biojet manufacture.
- Outlook for supply of advanced biojet (not from vegetable oils) is extremely limited; the very small volumes of bio-distillate type fuel that are projected to be available from known plants being constructed are more likely to be used in road transport due to the price premium available in EU and US markets.
- It will be very difficult to make a specific biojet manufacture business investment case due to sensitivity of airlines to fuel prices, lack of long-term robust policy or regulation supporting or requiring biofuel use, high capital costs, and feedstock availability, price and sustainability risks.
- A rational response of the aviation community to societal pressure and its own desire to reduce GHG intensity is to seek the maximum possible gains in efficiency and operational improvements. This is consistent with stated IATA goals.
- Airlines should also consider support for economic instruments such as carbon cap-and-trade schemes such that airlines effectively pay others to make GHG emission reductions on their behalf. Such schemes would need to be carefully constructed to address sufficiently the international competition issues that will arise within a global industry.

Post 2020

- Several technology routes exist to manufacture biojet from sustainable /non-food feedstock but all face challenges of either access to sufficient feedstock, or high capital and operating costs, or both.
- However, the IATA plan envisages major biojet volumes being used only after 2030; it is possible that there is a breakthrough in biojet manufacturing technology in one of the identified routes, or indeed another novel route, justifying the building of several biojet plants by this date, but there may still be an incentive to target the road fuel sector before placing volumes in the airline sector.
- In order to make robust investment cases in biojet manufacture and associated feedstock supply it will be necessary to have clarity on long term policy/regulation with regard to how a cost premium over petroleum jet would be met.
- Biojet manufacture will likely continue to compete with road biofuels for access to feedstock, and for attracting investment.
- It is expected that most advanced bio-distillate routes will likely have a better process yield to produce biodiesel than of biojet; this would likely lead to a higher price for biojet relative to biodiesel.
- Developments of biojet manufacturing technology should be linked to the development of advanced biodiesel/bio-distillate manufacturing technology; such technologies are critical for the future of lower carbon transport, and should be progressed and supported for the ultimate use in aviation, road and potentially other modes of transport. Aviation stakeholders can play a key role providing support.
- However, expectations should be set such that biojet is likely to be commercialised later than advanced biodiesel, due to the greater technical and economic challenges of bio-jet manufacture.

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