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Aviation biofuels: strategically important, technically achievable, tough to deliver

JONATHAN BOSCH[a], SIERK DE JONG[b], DR RIC HOEFNAGELS[b] AND DR RAPHAEL SLADE[c]

Headlines

- Globally, the aviation sector is expected to continue to expand. Deep carbon reductions will require a portfolio of mitigation strategies including sustainable fuels, fleet improvements, flight path changes, and emission offsets, if demand reduction is to be avoided.
- The global aviation sector recognises the need to decarbonise and is also interested in reducing its exposure to crude oil price volatility.
- Although the aviation industry's main trade association (IATA) has committed to carbon mitigation targets, the sector has few technical options to achieve the deep emissions reductions envisaged.
- Biomass-derived substitutes for kerosene jet fuel (biojet) are one of the only options for reducing airlines' direct carbon emissions, and may be one of the more strategically important uses of bioenergy in the long term.
- Conventional fossil jet fuel is expected to remain significantly cheaper than biojet in the medium to long term. Cost reductions and price support (e.g. carbon pricing) would be required to make biojet competitive.
- Procuring conventional agricultural commodities to produce biojet may have an impact on how land is used and the potential effects on sustainability are hotly debated. Biojet derived from waste materials and energy crops (e.g. short rotation coppice) are expected to prove less controversial.
- The quality of aviation fuels is tightly controlled. For a small number of production processes biojet is production-ready and internationally certified. Other processes are expected to have advanced to the early stages of commercialisation by 2020.
- Targeted policy initiatives would be needed in the short term to facilitate up-scaling of biojet production technologies, but the case has yet to be made that aviation biofuels should be prioritised over alternative economy-wide decarbonisation strategies in the drive towards a low-carbon future.

a Department of Chemical Engineering, Imperial College London, UK
b Copernicus Institute of Sustainable Development, Utrecht Universit, Netherlands
c Centre for Environmental Policy, Imperial College London, UK

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Background

Amidst the decades-long international effort to mitigate climate change, there has been mounting social and political pressure for the commercial aviation sector to play a bigger role in reducing global greenhouse gas (GHG) emissions.

Airline operations generated more than 781 million tonnes (Mt) of carbon dioxide (CO2) in 2015, representing two per cent of global man-made CO2 emissions[1]. Projections anticipate five per cent annual growth in airline passengers up to 2050[2], with emissions reaching 3,100 Mt annually in a high growth scenario[3]. Even with an aspirational goal of two per cent annual fuel efficiency improvements from 2020, as set by the International Civil Aviation Organization (ICAO), reductions achieved through efficiency gains will be significantly out-paced by annual growth in aviation passenger demand[4].

Although the Paris Climate Agreement[5] and its predecessor, the Kyoto Protocol (1997)[6], explicitly endorsed domestic aviation emissions reduction targets as part of national GHG inventories, the only mention of international aviation emissions in the 1997 agreement – the sector's largest contribution to global emissions[7] – was that Annex 1 countries should "reduce" emissions from international aviation under the leadership of ICAO. Recent developments within ICAO's remit have included two key international standards: the CO2 emissions efficiency standard (2013), and the Global Market-Based Measure (GMBM) scheme (2016). Both these standards passed major milestones in 2016, with the publication of ICAO's environmental report announcing the adoption of the GMBM and its planned introduction in 2020[4]. These schemes emerged from earlier aviation industry initiatives, in particular the International Aviation Transport Agency's (IATA) 2013 strategy for Carbon Neutral Growth 2020 (CNG 2020)[8,9].

Despite making progress, however, the sector still has a long way to go. If the aviation sector is to contribute to international policy ambitions to mitigate climate change then specific CO2 emissions per passenger-kilometre will need to be greatly reduced. Near-term options, however, are limited. Modern commercial aircraft are already extremely efficient, and the scope for engine efficiency improvements is incremental in such a mature technology. Furthermore, the take up of improvements is slow across the global fleet because the expected service lifetime of a modern aircraft is often 25 years or more[10]. The combined improvements of engine efficiency and air traffic management are estimated to represent an emissions reduction of 0.8% per annum over the period up to 2050 – equivalent to a carbon intensity reduction (i.e. grams of CO2 per passenger-km) of 30% from 2015 levels[11]. Deeper emissions reductions can only come from increased adoption of sustainable aviation fuels produced from biomass.

In addition to cutting carbon emissions, one of the key reasons stated by airlines for interest in biofuels is to reduce exposure to the price volatility of kerosene[12]. Several airlines, including KLM, Lufthansa and British Airways, amongst others, have been involved in the early stages of aviation biofuel development (hereafter referred to as biojet) by forming partnerships with biofuels manufacturers. There are also multi-stakeholder groups (including airlines, airports, aircraft manufacturers, governments, biomass and biofuel producers and suppliers) working together to boost biojet deployment. Several of these airlines, including KLM, United Airlines, Lufthansa and Cathay Pacific have already entered into long-term agreements with biofuel suppliers, but in 2016 these were still at modest volumes[13].

The current market for biojet is also small. Demand is limited by the considerably higher selling price of biojet compared with petroleum-derived kerosene, and supply is limited by the availability of industrial scale production facilities and alternative higher value uses of limited biomass feedstocks. Nevertheless, according to ICAO's Global Framework for Alternative Aviation Fuels (GFAAF), a total of 22 airlines had experimented with using alternative fuels for over 2,500 commercial flights up until July 2016, setting an impressive precedent for an industry that is barely a decade old[14].

The global fleet of 23,000 aircraft represents a past investment of hundreds of billions of dollars – possibly trillions, with life times of 20 years or more. This significant tied investment, long fleet life-cycle, and the stringent fuels certification process mean that airlines are reluctant to consider new fuels that are not 'drop-in' alternatives to current petroleum-derived jet fuel.

Greenhouse gas impacts of biojet production and consumption

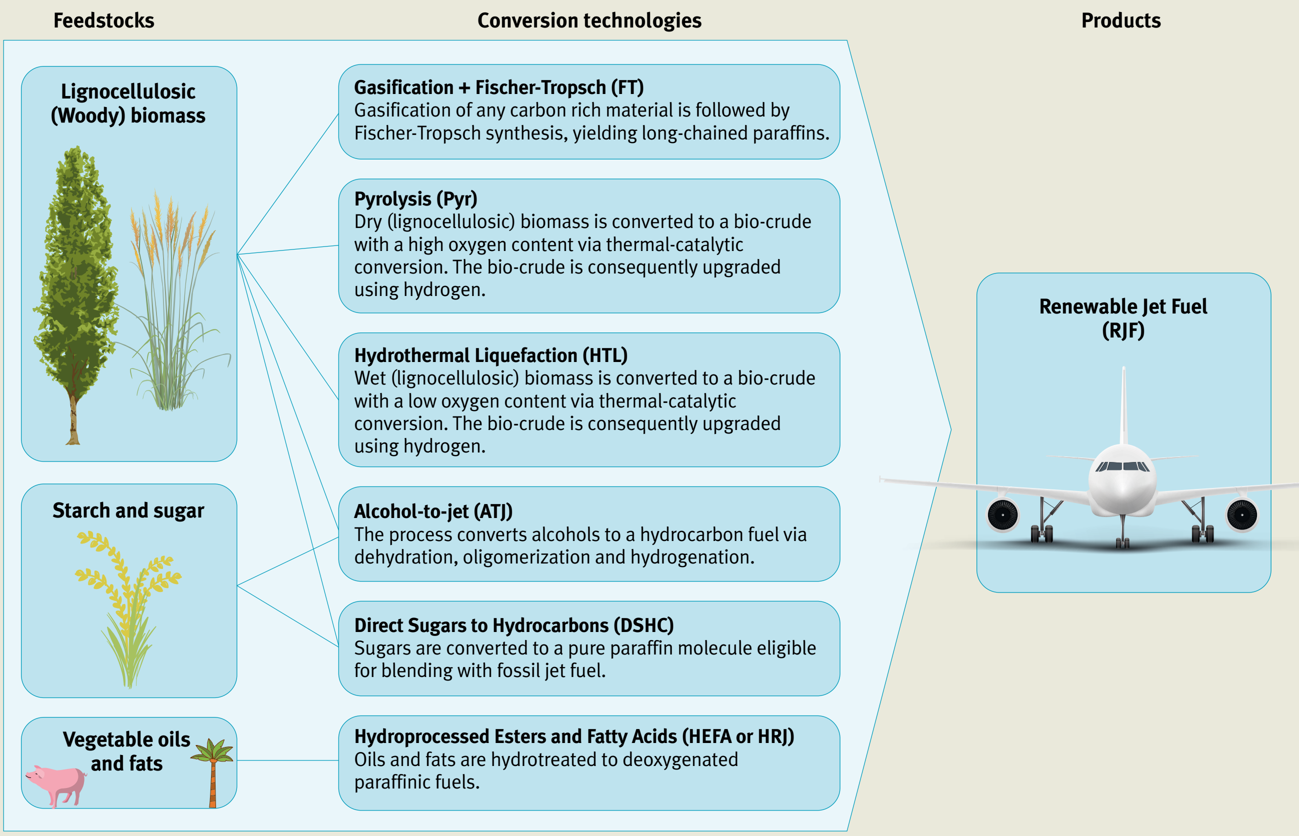
Manufacturing jet fuels from biomass involves growing (or acquiring) the biomass feedstock and upgrading it to a standardised fuel in an industrial processing plant. Comparing the GHG benefits of biojet with conventional jet fuel requires detailed lifecycle analysis that takes into account both production and processing stages.

Box 1: Biojet fuel pathways

Aviation biofuels (usually referred to as biojet or renewable jet fuel (RJF) are liquid fuels that can be produced from a wide range of biomass including vegetable oils, plant materials, and animal waste. Because plants sequester carbon from the atmosphere as they grow, over multiple cycles of growth, harvest, and re-growth, the net carbon emissions from using biojet can be less than the emissions from burning fossil fuels.

Aviation fuels are subject to strict compositional requirements beyond those required for road transport fuels. A high energy density is a key requirement as well as attributes such as lubricity and cold flow properties. To ensure the required properties are achieved biojet is currently blended with fossil fuel derived jet fuel.

Aviation biofuels can be produced via a number of processing technologies. Different feedstocks suit different process technologies depending on the physical and chemical structure of the biomass. The efficiency of conversion depends on the full process employed. For example, lignocellulosic feedstocks (e.g. forestry residues), could be converted using pyrolysis directly to liquid fuel, requiring upgrading via hydrogenation, or by gasification and Fischer-Tropsch synthesis. Starch and sugar crops can be used to produce alcohols which can then be converted to oligomers and dehydrated. More novel processes can convert sugars directly to hydrocarbons[84].



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GHG emissions for petroleum derived jet fuel

The majority of carbon dioxide emissions from fossil jet fuels (around 84%) are emitted when they are burnt in the engine. Only around 16% of emission are as a result of the production stages between oil well and fuel tank. Burning biojet also emits carbon dioxide, but under UNFCCC national reporting guidelines emissions at the point of use are recorded as zero in the energy sector. For biofuels, however, the emissions related to feedstock production and chemical processing may be substantial. A full consideration of the emissions from the whole production chain is known as well-to-wake analysis, which can be further split into two parts, well-to-tank (WTT) and tank-to-wake (TTW). An illustrative well-to-wake calculation is shown in Table 1.

Table 1: Example well-to-wake (WTW) CO2 emission for petroleum derived jet fuel[10]

	gCO2e/MJ
well-to-tank	14.3
tank-to-wake	73.2
well-to-wake	**87.5**

GHG emissions for biomass derived jet fuels

Depending on the combination of feedstock source and fuel conversion technology, biojet pathways can reduce lifecycle emissions by between 20% and 95% when compared with petroleum-derived jet fuel[15,10], although the extent of reductions are still the subject of much debate[16, 17].

When calculating the emissions intensity of biofuels the emissions associated with feedstock production often make a significant contribution to the overall GHG intensity of the biofuel. Production emissions are generated from diesel used for harvesting, fertiliser production, N_2O emissions from soils, emissions from harvesting machinery, and emissions associated with land use change. Typically, feedstocks derived from agricultural and forestry residues, and also from municipal wastes, have lower life-cycle GHG emissions than those derived from dedicated energy crops.

For some pathways full-cycle emissions reductions in excess of 90% have been reported[7,10]. For example, energy crops and forestry residues converted via gasification and Fischer-Tropsch (FT) synthesis can result in very low lifecycle GHG emissions despite the energy intensity of the process being relatively high; this is because the process energy is derived from the biomass itself and emissions associated with feedstock production are low. In contrast, lifecycle GHG savings for biojet produced from conventional oil crops (via the HEFA pathway) are modest because of the high GHG emissions associated with feedstock production and the production of hydrogen for upgrading the fuel[10].

Table 2: Well-to-wake comparisons, alternative biojet fuel routes compared to conventional jet fuel[10, 18]

Route	Feedstock	Biojet GHG emissions gCO2e/MJ	Fossil jet gCO2e/MJ	Savings CO2e %
Gassification and Fischer-Tropsch	Energy crops	9-13	87.5	85-90
	Forestry residues	6		95
Pyrolysis	Forestry residues	22-40		54-75
Alcohol to jet	Corn	55		37
	Corn stover	35		60
	Sugar cane	26		70
Direct sugar to hydrocarbons (DSHC)	Sugar cane	72		18
Hydroprocessed esters and fatty acids (HEFA)	Oilseed rape, soy	40-108		20-54
	Jatropha	55		37
	Camelina	47		46
	Used cooking oil	27		69

The aviation sector is aware of the sustainability impacts created by the use of dedicated energy crops for biojet fuels, as well as their potential competitive tensions with biofuels for road transport and agricultural crops. Members of the Sustainable Aviation Fuel Users Group — stakeholders representing 33% of commercial aviation fuel demand — have signed a sustainable development pledge to develop alternative jet fuel options which are "non-competitive with food and where biodiversity impacts are minimised"[19]. Furthermore, legislation such as the European Union indirect land use change (ILUC) directive and USA Renewable Fuels Standard recognise constraints on land use for biofuel production. Nevertheless, the sustainability of using biofuels remains a contentious and politically sensitive issue[20].

Making the transition to aviation biofuels

The introduction of biojet fuels at a commercial scale depends on a range of factors related to international standards, certification, technology readiness, and industrial relations.

Performance requirements and international standards

All biojet fuels must be 'drop-in' replacements for conventional jet fuels. Nevertheless, before biojet can be introduced into existing jet fuel supply chains, new fuels must demonstrate that they meet American Society for Testing and Materials (ASTM) specifications and gain ASTM certification following a rigorous programme of testing. Fuels must reach performance benchmarks that meet the operational and safety requirements of existing jet engines. These include properties such as energy content, freeze point, thermal stability, viscosity, combustion characteristics, lubricity, material compatibility, and other requirements specific to biojet.

Certification of jet fuels is governed by ASTM 1655[21] and equivalently, Defence Standard 91-91[22] of the UK Ministry of Defence. Certification of new fuels can be a lengthy and costly process involving not only the fuel standards body, but importantly, the new fuel sponsor, and the aircraft engine and airframe manufacturers. The first examples of synthetic fuels were liquid fuels from coal; Sasol's fuel blend, certified in 1999, was 50% petroleum and 50% coal-derived FT jet fuel and took seven years to be fully certified. There are, however, still no examples of 100% synthetic jet fuels in the global supply chain, although a fully synthetic fuel was added to the ASTM standard in 2009[10], and a number of 100% drop-in biojet fuels are in development.

Since conventional fuel is produced by refining petroleum crude, its composition varies depending on the raw crude, but is made up of paraffins, isoparaffins, napthenes and aromatics in fairly consistent proportions. Biofuels on the other hand, are derived from a diverse range of feedstocks. As a consequence, the composition and properties are variable, making it potentially costly to reach ASTM standards. For example, biofuels synthesized from gasified biomass and converted to liquid fuel via the FT process lack desirable napthene and aromatic components. These missing components can be brought up to acceptable levels, either by adding a costly and energy intensive isomerisation process step to improve the freezing point, or by blending the biofuel with petroleum jet fuel to a level where fuel performance specifications are met – typically at least a 50% fossil fuel portion for synthetic FT jet fuel[10]. Currently there are five synthetic fuel blends derived from different pathways certified for commercial use.

Some alternative biojet fuel pathways may reduce the requirement for fuel blending, but these are in the early stages of development and require additional energy input via upgrading processes, so their introduction is not foreseen in the short term. Examples include 100% drop-in products from ARA-Chevron Lummus Global[23] and Swedish BioFuels[24].

The Fuel Readiness Level (FRL), adapted from the Technology Readiness Level (TRL) scale already used in aerospace applications, can chart the development of new production pathways for biojet fuels. There are a number of technologies expected to reach demonstration and certification stages by 2020, with 16 currently being reviewed by ASTM[14]. Although it is useful to understand where on the FRL scale a fuel is positioned, it does not necessarily tell us how sustainable that production pathway is, either commercially or environmentally. HEFA, for instance, is a well-developed technology but it relies on vegetable oil feedstocks, the procurement of which (unless produced from waste material) may result in damaging land management practices, particularly if large volumes are needed in the future. Figure 1 shows the relationship between FRL and production scale. Some fuel pathways have proven production capability to a high FRL but have limited proven potential to scale production to effective levels due to feedstock availability. For example HEFA is advanced in FRL (between 7-9 for different products), but relies on a limited supply of oil feedstock from conventional crops or used cooking oil. ATJ and DSHC could theoretically upscale by using lignocellulosic feedstocks but these technologies are not currently in development.

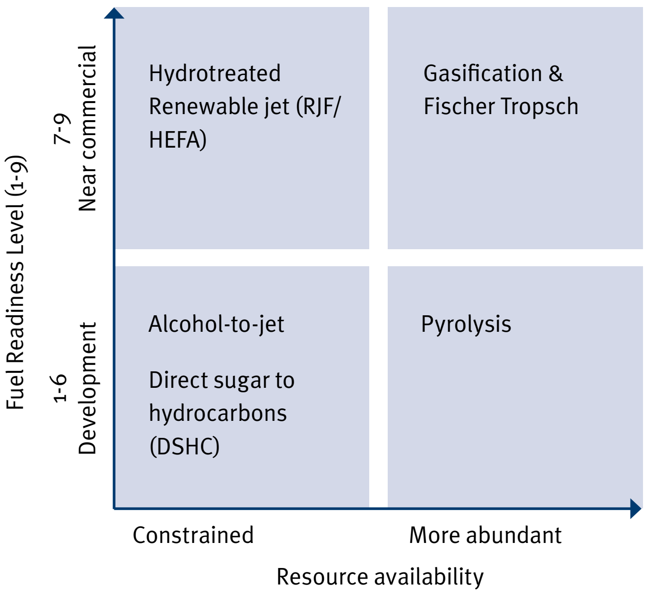

Figure 1: Scope for high volume commercial manufacture. The vertical axis represents the progression in FRL from 1 to 9. The horizontal axis represents scale of resource availability.

Box 2: Fuel Readiness Level

The Fuel Readiness Level (FRL)[64] approach is based on NASA's Technology Readiness Level (TRL) framework. It provides a descriptive hierarchy to indicate the progression of a technology towards commercialisation. Unlike TRL, the FRL method makes reference to the specific risks involved in developing fuels related to the fuel's composition, chemistry, and compatibility with fuelling infrastructure and aircraft[65].

An assessment of biofuel sustainability[63] found it took three to five years to progress one FRL, based on industry experience and project consortium timelines. Assuming this rate of progression, biofuels might expect to advance by one level by 2020. Progress is, of course, dependent on continued research and investment.

Table 3: Fuel Readiness Level (FRL)[64, 25]

	Level	FRL description	Toll gate
Commercial deployment	9	Production capability established	• Full-scale plant operational
	8	Commercialisation	• Business model validated for production • Airline purchase agreements secured • Plant-specific independent greenhouse gas assessment conducted to internationally accepted methodology
Certification processes	7	Fuel approval (certification)	• Fuel listed in international standards
	6	Full-scale technical evaluation	• ASTM certification tests conducted: fitness, fuel properties, engine and components testing
Technological R&D	5	Process validation	• Scaling from laboratory to pilot plant
	4	Preliminary technical evaluation	• System performance and integration studies • Specification properties evaluated
	3	Proof of concept	• Lab scale fuel sample produced from realistic feedstock • Energy balance analysis executed for initial environmental assessment • Basic fuel properties verified ted in international standards
	2	Technology concept formulated	• Feedstock and complete process identified
	1	Basic principles	• Feedstock and process principles identified

Recent biojet initiatives

Many airlines and biofuel manufacturers have experimented with partnerships including Cathay Pacific with Fulcrum, United Airlines with AltAir, KLM and Lufthansa with Neste, TOTAL with Air France, as well as involvement by Finnair, Interjet, Aeromexico, Iberia, Thomson Airways, Air France, Alaska Airlines, Thai Airways, LAN, Qantas, Jetstar, Porter, Gol, Air Canada, bmi, Nextjet, SAS, Norwegian and Hainan Airlines[25, 26]. Some of the airlines involved have already concluded long-term offtake agreements with biofuels suppliers, but these mostly begin during or after 2016, and constitute volumes below 100,000 tonnes per year. In September 2017 ICAO reported that three airports were regularly distributing biojet, reaching around 40,000 commercial flights[1].

In addition to these partnerships, several multi-stakeholder groups are currently working together to boost the deployment of biojet. A non-exhaustive list of multi-stakeholder groups are shown in Table 4[27]. Each group, however is constituted differently depending on stakeholder interests. For example, the Initiative Towards Sustainable Kerosene for Aviation (ITAKA) is a consortium of aviation and fuel companies focussing on supply chain development, while the Commercial Aviation Alternative Fuels Initiative (CAAFI) is an all-encompassing multi-stakeholder platform with US government agencies, researchers, as well as airlines and original equipment manufacturers (OEM).

Making the business case

Aviation biofuels are more expensive than conventional jet fuel[28]. As fuel costs make up a large proportion of airlines' operating costs, from a financial perspective biojet does not provide sufficient benefits to justify changing fuel procurement practices. The volatility of kerosene jet fuel prices – strongly linked with the price of crude oil – acts as one incentive for airlines to move to biojet fuel[12]. However, since late 2014, jet fuel prices have fallen from a long-term average above US$0.77 per litre to a 2017 monthly average below US$0.42 per litre (a 45% reduction)[29]. There is hence a reduced incentive for airlines to invest in alternative fuel pathways, although there is limited evidence that airlines have reduced their planned biojet commitments.

Table 4. Overview of international multi-stakeholder biojet networks[27]

Name	Scope	Stakeholders	Objective
Sustainable Aviation Fuel Users Group (SAFUG)	International	Airlines	Stakeholder platform, sustainability
Initiative Towards Sustainable Kerosene for Aviation (ITAKA)	European	Biojet and feedstock producers, suppliers, airports, airlines, knowledge institutions	Supply chain development
European Advanced Biofuels Flight Path Initiative	European	OEMs, airlines, biojet and feedstock producers, European commission	EU platform supports the deployment of 2 million tonnes of biojet in 2020
Commercial Aviation Alternative Fuels Initiative (CAAFI)	US	OEMs, airlines, fuel suppliers, universities, US govt. agencies	Stakeholder platform
Aliança Brasileira para Biocombustíveis de Aviação (ABRABA)	Brazil	OEMs, airlines, biojet and feedstock producers	Stakeholder platform, supply chain development
Aireg	Germany	OEMs, airlines, biojet and feedstock producers, knowledge institutions, German govt. agencies	Stakeholder platform, supply chain development
Bioqueroseno	Spain	OEMs, airlines, biojet and feedstock producers knowledge institutions, Spanish govt. agencies	Stakeholder platform, supply chain development
Flightpath to sustainable aviation	New Zealand/ Australia	Technology providers, OEMs, airlines, knowledge institutions, sector organisations, government agencies	Study on regional potential
Australian Intiative for Sustainable Aviation Fuels (AISAF)	Australia	United States Study Centre, Baker & McKenzie, Boeing Australia, CSIRO, GE, Qantas, Australian govt., Virgin Australia	Strategic advisory group. Implementation of 'Flightpath to sustainable aviation'

Biojet technologies also compete with high value road transport fuels whose specification and upgrading requirements are not as strict. Biomass gasification and Fischer-Tropsch, and ATJ pathways produce fuels with a desirable composition for road transport[30], and therefore command a price premium, particularly in jurisdictions with strict road fuel standards such as the US and the EU[31]. HDCJ, or 'pyrolysis', pathways are also well suited to high value chemical commodities[32], acting as a strong disincentive to co-produce aviation fuel[33]. As a result many stakeholders make the case that biofuel technologies will require regulatory protection in the short term in order for them to become cost competitive later on[34].

Cost reduction opportunities

The make-up of biofuel production costs offers an indication of the potential for long term cost reductions. Figure 2 shows the current representative minimum fuel selling prices (MFSP) with respect to their cost composition for the main biojet technology pathways. Most notably, high feedstock costs may prevent some biojet products from becoming price competitive because the feedstock cost may already exceed the current petroleum-derived jet fuel price.

The biomass gasification-Fischer-Tropsch pathway is a capital-intensive technology with capital expenditure accounting for between 50 and 75%[35] of total production costs, while the feedstock represents 10-35%[30]. The Fischer-Tropsch process, used in a range of biomass to liquid conversion processes, has significant scope for economies of scale[36, 37], where increasing capacity has shown to significantly reduce capital costs for several relevant synthetic fuel technologies[30]. However, the process is only cost-effective at a large scale, presenting a challenge in relation to feedstock logistics and investor risk[38].

For HEFA fuels, feedstock costs are a significant proportion of total costs, and unlikely to fall. A common feedstock for biofuels is used cooking oil, but in the EU it is estimated that from the approximately one million tonne[39] that is already collected, up to 90% is already used for biodiesel production[25]. In addition, while global supplies of vegetable oils exceed 180 million tonnes annually[40], the aviation industry is reluctant to pursue large scale production because of the perceived environmental sustainability concerns and competition with food production[19].

The scope for feedstock production efficiencies depends both on growing more, and on long-term improvements in crop yield. In some jurisdictions (e.g. the EU). Increasing land cultivation is limited by legal barriers to land exploitation for biofuels[41]. Industry may also be unwilling to pursue these pathways in the face of sustainability concerns[19]. For feedstocks derived from waste products (e.g. agro-waste, used cooking oil, municipal waste, etc.), efficient scaling up will depend on the availability and proximity of feedstock sources in relation to the appropriate processing facilities. Pyrolysis-based processes may be better suited to small scale production – matching the scale and logistics of feedstock supplies[42].

The potential for biorefineries to take advantage of scale economies is constrained by the inherent difficulties in working with a biomass feedstock. Feedstocks in lignocellulosic form are bulky and have low energy densities, making them

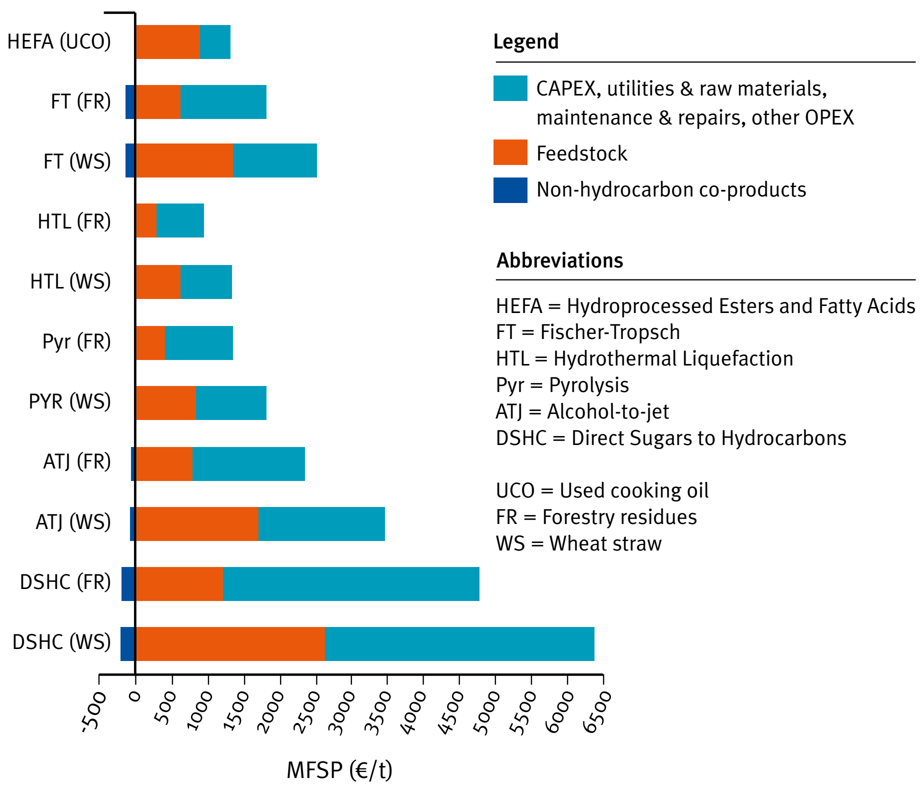

Figure 2: Minimum fuel selling price (MFSP) for biojet for a number of conversion pathways. Cost estimates are based on a discounted cash flow rate of return (DCFOR). The MFSP reflects a cost-price level at which the fuel needs to be sold to achieve a zero equity net present value (NPV)[38]. The MFSP for some fuels is less than the total costs because of the sale of non-fuel products, represented by the negative portion of the bar.

difficult and costly to transport. This represents a real limit to maximum plant capacity, since distance and viability of transport connections has to be considered[36, 37]. There is some scope for improving the feasibility of large scale gasification-Fischer-Tropsch plants by pre-processing the feedstock before transportation. Pretreated and densified biomass is cheaper to transport than the raw material, and can therefore be transported further. Alternatively, plants designed or refitted to process fossil fuel feedstocks in parallel could help to subsidise the total feedstock costs, although this would increase the GHG emissions of the fuel produced.

The policy landscape – government and industry initiatives

The policy environment for renewable fuels is complex, as regional and national policies, as well as industry initiatives, compete and interact with one another in ways that may not be easy to anticipate. Box 3 lists the type and scope of policy options available to target biojet production and markets. Table 5 shows an overview and timeline of currently adopted policies.

International policy

Initiatives in support of mitigation and decarbonisation in the aviation industry are well represented in current policies. ICAO has developed two measures for emissions mitigation over the last few years, both of which should lend indirect support to the development of biofuels.

The global market based mechanism, Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), was adopted in October 2016, and set to enter into force in 2020[43]. The scheme implements a carbon-offsetting mechanism, aiming to stabilise aviation CO_2 emissions at 2020 levels through to 2036. ICAO estimates that 464 Mt of CO_2 offsets will be required in 2036 to account for the emissions increases from a 107% growth in international air traffic[44]. ICAO plans to credit biofuels “that cut emissions beyond set thresholds, measured on a net lifecycle emissions basis”[45]. Commentators argue that ICAO should stipulate threshold GHG reductions for different alternative fuels to incentivise fuels that offer genuine GHG reductions[43].

In February 2016, ICAO introduced the world’s first CO_2 efficiency standard after six years of negotiation, supported by industry and environmental experts. This standard applies to all new commercial and business aircraft delivered after 1 January 2028 and will require, on average, a four per cent reduction in cruise fuel consumption compared with 2015 deliveries[46]. The measure is designed to be complimentary to other measures being brought forward by the ICAO council, but offers limited incentive for biojet investment if airlines believe that engine efficiency improvements alone can deliver the CO_2 efficiency targets.

ICAO has recognised the need to promote and facilitate the deployment of biojet fuels, and in this regard established the Sustainable Alternative Fuels for Aviation expert group, whose work has been to identify the challenges to the deployment of sustainable fuels and the possible solutions that states might use to address them. The group’s recommendations were considered by the council and made available in the Global Framework on Aviation Alternative Fuels[47].

Box 3: Policy landscape

Industry-led targets:

- IATA and ATAG led targets with industry adoption via resolutions or as signatory to commitments.

National policy and regulation:

- Environmental regulation to limit emissions of industries;
- Regulating industry to produce minimum volumes of biofuels (e.g. Renewable Fuel Standard);
- Subsidisation and tax incentives of fuel production industry;
- Federal and/or government department commitments to invest or plan purchase agreements of biofuels (e.g. US Department of Defence investment commitments).

Market-based mechanisms:

- Emissions offsetting to other industries by allocating and purchasing credits to emit;
- Possible at international (e.g. ICAO CORSIA), supra-national (EU Emission Trading System), national (e.g. China Emissions Trading Scheme) levels.

International treaties:

- Negotiated through the UN, e.g. UN Framework Convention on Climate Change
- E.g. ICAO’s new CO_2 efficiency standard, ICAO sector-specific agreements.

EU directives

Two major directives of the European Union support biojet fuels: the EU Emissions Trading System (EU ETS) and the Renewable Energy Directive (RED).

The EU ETS is a cap and trade scheme which was launched in 2005 and aimed to limit GHG emissions from power plants and industrial facilities, but included no explicit provision for international aviation in its first phase. In the second phase, from 2012, all civil aircraft using airports in the European Economic Area (EEA) and European Free Trade Association states were counted in ETS – regardless of where the flight started – with a zero emissions factor applied to biojet fuels. However this policy proved divisive and several lawsuits were levelled at the EU in the initial period, leading to the law being effectively put on hold to allow ICAO to design its own market based mechanisms. Before its suspension however, aviation stakeholders cited ETS as one of the most important drivers for biojet development[48].

The speed and scale at which any carbon price mechanism, such as the EU ETS, can achieve investment and innovation depends on the strength of the price signal created by the market. A credible and long-term incentive is required to shift investment decisions.

The EU RED was first adopted in 2009[49], with the Indirect Land Use Change (ILUC) directive[41] added in 2015. The RED mandates that 20% of energy consumption in the EU should be sourced from renewable sources by 2020, including ten per cent of all energy used for transport. The ILUC amendment limits the share of biofuels from crops grown on agricultural land that can be counted towards 2020 renewable energy targets to seven per cent. It further sets an indicative 0.5% target for advanced biofuels (such as biojet) as a reference for national targets, and allows biofuels to be counted double towards the EU's 2020 target. The successor to the RED (REDII) is a renewable energy package for the period 2020-2030 and is expected to cut the maximum contribution of conventional biofuels from seven per cent in 2021 to 3.8% in 2030, but the final legislation is still in negotiation[50].

National policy

Notable national polices supporting biojet fuels can be found in the US, China, and Indonesia.

In the US, much of the development of renewable fuels has been pioneered by the US Army, Air Force and Navy, with targets for alternative fuel consumption forming part of their respective energy plans since 2012[51, 52]. The US Air Force has set a goal of cost-competitively acquiring 50% of its domestic aviation fuel requirements from alternative fuel blends by 2016. The Navy has similar targets for 2020[53]. The US's Energy Policy Act 2005 established the Renewable Fuel Standard (RFS) which requires that a minimum volume of biofuels be used in national transportation fuel, heating oil, or jet fuel. Renewable fuels were defined as biomass-based diesel, cellulosic biofuels and advanced biofuels. Similar legislation in the Netherlands (Transport Biofuels Act 2007) requires petrol and diesel producers and suppliers to deliver a certain percentage of their fuel sales (in energy value) in the Netherlands in the form of biofuels. The requirement can also be traded between suppliers in the form of bio-tickets. The legislation imposes an incrementing minimum biofuels target, which in 2016 was seven per cent[54].

In China, a nationwide emissions trading scheme (ETS) has been in development for several years. During a pilot scheme, Shanghai was the only region to have incorporated the aviation sector. The national scheme is scheduled to launch in the near future with the aviation sector included (civil aviation, passenger transport, air cargo and airports)[55].

In 2013, Indonesia become the first country to legally oblige the aviation sector to use biojet fuels in the jet fuel mix as part of its Green Aviation Initiative[56]. The target aims to reduce GHG emissions of the energy and transport sectors together by 26% up to the year 2020, and stipulates that aviation should contribute by introducing two per cent alternative fuels into the aviation fuel mix by 2016, and three per cent by 2020. It is not clear whether Indonesia is on track to meet its 2020 target, but it does have biofuel development experience in the land transportation sector.

Industry-led targets

The aviation industry has developed its own strategy to combat climate change, in parallel and in partnership, with the ICAO. These initiatives are led by the International Air transport Association (IATA) and the Air Transport Action Group (ATAG).

IATA and ATAG are supportive of a "basket of measures", as demonstrated by IATA's Four-Pillar Strategy which was proposed in 2007 at the ICAO Assembly and adopted by the entire industry in 2008 at the Aviation and Environment Summit[57]. The strategy suggests four key targeted areas to tackle CO_2 emissions in air transport: technologies, operations, infrastructure and economic instruments. Large contributions from biofuels are foreseen within the technology theme, but no explicit policy for biofuels has been brought forward.

In 2013 an IATA resolution Carbon Neutral Growth 2020[9] committed to:

- A 1.5% average annual improvement in fuel efficiency from 2009 to 2020;
- Carbon-neutral growth from 2020;
- A 50% absolute reduction in carbon emissions by 2050.

IATA also publishes an alternative fuels annual report[13] and hosted its first international Alternative Fuels Symposium in 2015.

High-level advocacy and networking organisations can play a significant role in giving this emergent sector better influence in the allocation of resources, promoting supportive policy, and in developing viable markets[58]. Stakeholders sampled in one study[12] believed that IATA can "coordinate efforts to raise advocacy for the [biojet] sector, and convey the message to policymakers in order to shape supportive policy and break down deployment barriers".

Despite this breadth of activity, there are currently few policies dedicated to supporting biojet take-up at a large scale. Some policies, especially market instruments such as the emissions trading systems, pursue a least-cost pathway across sectors to achieve emissions reductions, consequently they are unlikely to support biojet use in the near term. National policies mandating biofuels use in the fuels supply chain, for instance Indonesia's Green Aviation Initiative, have yet to demonstrate their efficacy in developing the large-scale supply chains required.

Conclusions

Introducing biojet fuels as a significant share of the global jet fuel supply represents one of the few opportunities to mitigate commercial aviation carbon emissions over the long term. Innovations in engine efficiency, air traffic management and other operational efficiencies are forecast to contribute only 0.8% in emissions reductions annually up to 2050, despite ambitious targets from the industry to improve CO_2 efficiency standards.

It is likely, however, that the realisation of economically viable biojet fuels will only come about with a substantial increase in the scale and number of production facilities, expediting technology learning and associated cost reductions. Stimulating this change is expected to necessitate substantial policy incentives to bridge the price gap between kerosene and biofuels.

Aviation industry presentations describe a commitment to decarbonisation and suggest that alternative fuels will additionally provide them protection from crude oil price volatility. However, it is clear that the current availability and price of biojet is not incentivising airlines to make significant purchasing commitments. Industry-led targets also do not currently include commitments to biojet investment, and offtake agreements amount to volumes that do not make significant mitigation impacts.

Biojet fuels, however, are already established as an alternative jet fuel option with the possibility of significant lifecycle emissions reductions (depending on feedstock and process). But because conventional jet fuel remains significantly cheaper than biojet, price support and cost reductions (e.g. through technological learning) would be required to make biojet competitive.

Biofuels derived from conventional agricultural commodities, or those displacing current agricultural land, may have significant impacts on land use when compared with biojet derived from waste products. Sourcing biomass feedstocks sustainably continues to provoke controversy and this will undoubtedly apply to aviation at the volumes required to meet industry aspirations for carbon neutral growth.

There are many feasible pathways for biojet fuel production but cost fundamentals may limit the economic viability of some routes. Development costs and stringent certification procedures remain significant barriers to the timely introduction of new fuels to market with the result that it may be easier and cheaper to produce road transport fuels instead.

Policy and industrial initiatives have made some recent breakthroughs on commitments to CO_2 emissions reductions, but there remains an absence of biojet-specific targets and incentives to deliver on medium term emissions mitigation targets. More targeted incentives would be needed in the short term to facilitate the up-scaling of biojet technologies. The case is yet to be made as to whether biojet is a top priority for achieving carbon reductions.

Table 5. Timeline of policies targeting GHG emission reductions in the aviation sector.

Implementing organisation	Policy name	Goals/description	Adopted
ICAO	Global Market Based Mechanism (GMBM) [A39-3]	• Resolution for GMBM adoption, to be introduced by 2020	October 2016
UNFCCC	Paris Agreement [1/CP.21]	• Domestic aviation included within national GHG inventories and eligible to contribute to the Intended Nationally Determined Contributions. • No mention of international aviation	October 2016
EU	Indirect Land Use Change Directive	• Amendments to the EU RED targets • Contribution of biofuels from 'food' crops capped at 7%. • Indicative target of 0.5% for advanced biofuels. • Advanced biofuels double-counted towards overall targets.	September 2015
ICAO	Assembly Resolution [A38-18]	• Aspirational goal to stabilise net CO2 emissions from international aviation at 2020 levels.	February 2013
EU	EU Emissions Trading Scheme (ETS)	• International aviation added to EU ETS and subsequently suspended • ETS amended to include only flights within the EAA for the period 2013-2016	November 2012
ICAO	Programme of Action on International Aviation and Climate Change [A37-11]	• To achieve a global average fuel efficiency improvement of 2% per annum until 2020 • Aspirational goal to improve average fuel efficiency by 2% per annum from 2021 to 2050	October 2009
EU	Renewable Energy Directive (RED)	• 10% of all energy consumed by transport in the EU to be sourced from renewable sources by 2020	
IATA & ATAG	Joint adoption of environment targets by ATAG Board and IATA	• To improve fuel efficiency by an average of 1.5% per year from 2009 to 2020 • To stabilise emissions from 2020 with carbon-neutral growth • Aspirational goal to reduce net emissions from aviation by 50% by 2050 compared to 2005 levels	June 2009
ATAG	Aviation Industry Commitment to Action on Climate Change	• Commitment to pursue the IATA's Four-Pillar strategy	June 2008
IATA	Four-Pillar Strategy	Strategy proposed and unanimously supported at the ICAO Assembly: 1. Improved technology, including the deployment of sustainable low-carbon fuels 2. More efficient aircraft operations 3. Infrastructure improvements, including modernised air traffic management systems A single global market-based measure, to fill the remaining emissions gap	October 2007
EU	EU Emissions Trading Scheme (ETS)	• Establishing a scheme for greenhouse gas emissions allowance trading within the EEA • Introduced in 2005	October 2003
UNFCCC	Kyoto Protocol	• Domestic aviation emissions included within national GHG inventories and subject to national targets • Annex 1 (developed) countries should 'reduce' emissions from international aviation • Responsibility for coordinating action on international emissions assigned to the ICAO	December 1997

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Glossary

CORSIA – Carbon Offsetting and Reduction Scheme for International Aviation, a scheme for reducing aviation emissions developed under the auspices of the International Civil Aviation Authority.

Feedstocks – the raw material used to manufacture the biofuel.

Hydrolysis – a process that uses water to break down biomass into sugar and lignin fractions.

Market-based mechanism – a policy or tool that uses market forces to encourage reductions in greenhouse gas emissions by e.g. setting up a new market to create value for emissions reductions.

Pyrolysis – a process that uses heat to decompose biomass in the absence of oxygen.

Lignocellulosic biomass refers to plant dry matter. The name refers to its chemical composition: carbohydrate polymers (cellulose, hemicellulose) and an aromatic polymer (lignin).

Definitions of the processes used to manufacture biofuels for aviation can be found in Box 1.

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About the authors

Jonathan Bosch is a post graduate researcher in the department of Chemical Engineering at Imperial College London. He has a Masters' degree in mechanical engineering and spent the early part of his career in research and development for the LHC particle accelerator at CERN. His current research is focused on estimating global renewable energy potentials, considering the time variance and spatial dependence of the renewable resource. The outputs are aimed at improving global energy systems scenarios to find economic pathways to a sustainable energy future. He is supported by a Grantham Institute PhD scholarship.

Sierk de Jong is a PhD candidate at the Copernicus Institute of Sustainable Development (Utrecht University), focusing on the economic and environmental feasibility of renewable jet fuel as an instrument to reduce the climate impact of the aviation sector. Sierk also holds a position at SkyNRG where he works on the realization of renewable jet fuel supply chains.

Dr. Ric Hoefnagels is a Junior Assistant Professor at the Copernicus Institute, Utrecht University. He is involved in bioenergy related projects including the EU H2020 funded project AdvanceFuel. He was also a member of multiple national projects and EU funded projects including Re-Shaping, RENJET, Biobench, Dia-Core and BioSustain.

Dr. Raphael Slade is a Senior Research Fellow at Imperial College London. His research focusses on the economic, technological and policy aspects of producing energy and materials from biomass, the strategic responses to increasing natural resource scarcity, and the environmental implications of the transition to a low carbon energy future.

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