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MITIGATING INTERNATIONAL AVIATION EMISSIONS

RISKS AND OPPORTUNITIES FOR ALTERNATIVE JET FUELS

Sammy El Takriti, Nikita Pavlenko, and Stephanie Searle

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

www.theicct.org

communications@theicct.org

BEIJING | BERLIN | BRUSSELS | SAN FRANCISCO | WASHINGTON

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For additional information:
International Council on Clean Transportation
1225 I Street NW Suite 900
Washington, DC 20005 USA

communications@theicct.org | www.theicct.org | @TheICCT

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EXECUTIVE SUMMARY

International aviation is expected to expand at a considerable rate—as much as 4.3% annually—in the next several decades. To mitigate the corresponding increase in greenhouse gas emissions, the International Civil Aviation Organization (ICAO) introduced the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), with the aim to achieve carbon-neutral growth after 2020 through a set of measures that include technological improvements, operational improvements, and substituting jet fuel with alternative jet fuels. Any remaining obligations would be met with the purchase of carbon offsets. ICAO forecasts that meeting the ambitious CORSIA goals would necessitate that over half of the reductions come from a combination of alternative jet fuels and carbon offsetting.

This study evaluates the potential opportunities and risks for alternative jet fuels (AJFs) by assessing their sustainability, cost, and constraints to deployment. AJFs are substitutes for petroleum-derived jet fuel, which can be produced from different feedstocks and through several pathways, using biological, chemical, and thermal processes. The range of feedstocks to produce AJF includes starchy crops, sugary crops, lignocellulosic crops, oily crops, waste fats, oils and greases, agricultural residues, forestry residues, microalgae, municipal solid waste, waste industrial gases, and carbon dioxide (CO_2). Five different AJF products have been certified for blending with petroleum jet fuels.

Not all AJFs provide substantial greenhouse gas (GHG) reductions over petroleum jet fuel; in fact, many feedstocks and pathways provide minimal, if any, carbon savings. Like all biofuels, AJF production leads to direct emissions from fuel and feedstock processing and transport and use of agricultural inputs, as well as indirect emissions from market-mediated land-use change (LUC) for land-based feedstocks. According to some sources, life-cycle GHG emissions from alternative fuels can be up to 80% lower than traditional fossil jet fuel emissions (ATAG, 2016; IATA, 2016a; ICAO, 2016b). Considering the values reported in the literature, this percentage represents a relatively small share of the overall selection of feedstocks and pathways.

This study includes a literature review of AJF life-cycle assessment data that highlights several important trends. AJF produced from sugar and starch feedstocks deliver only a small GHG benefit, whereas those made from vegetable oil-based feedstocks tend to have a higher carbon intensity than conventional jet fuel when LUC effects are taken into consideration. Only AJF from lignocellulosic and waste feedstocks are consistently shown to provide substantial emission reductions compared to conventional jet fuel. These findings are broadly consistent with life-cycle GHG emissions of road biofuels and, in particular, with the recent study using the GLOBIOM (Global Biosphere Management Model) model to estimate direct and indirect land-use change (ILUC) emissions (Valin et al., 2015).

The total potential GHG savings achieved from biofuels in the aviation sector depends on the quantities of feedstock that could be used globally in a sustainable manner. Lignocellulosic feedstock and waste are the most promising options, but the supply of wastes as well as some types of lignocellulosic material, such as agricultural and forestry residues, is relatively inflexible and limited by competing uses from other sectors.

Figure A shows that even after accounting for emissions reductions from technology and operations improvements, the available quantities and types of feedstocks for AJF suggest that fuel-switching alone is unlikely to meet ICAO's goal of carbon-neutral growth from 2020 onward. Although estimated demand for jet fuel amounts to 24–37 EJ in 2050, assessments show that the absolute maximum amount of lignocellulosic biofuel that could be available for the aviation sector is around 4 EJ in 2050, resulting in emission reductions up to around 360 million tonnes of CO_2. The actual amount of low-carbon AJF that will be available is likely much lower. Strikingly, in the worst-case scenario, the use of high-GHG feedstocks, such as palm oil, could actually *increase* emissions by as much as 10%.

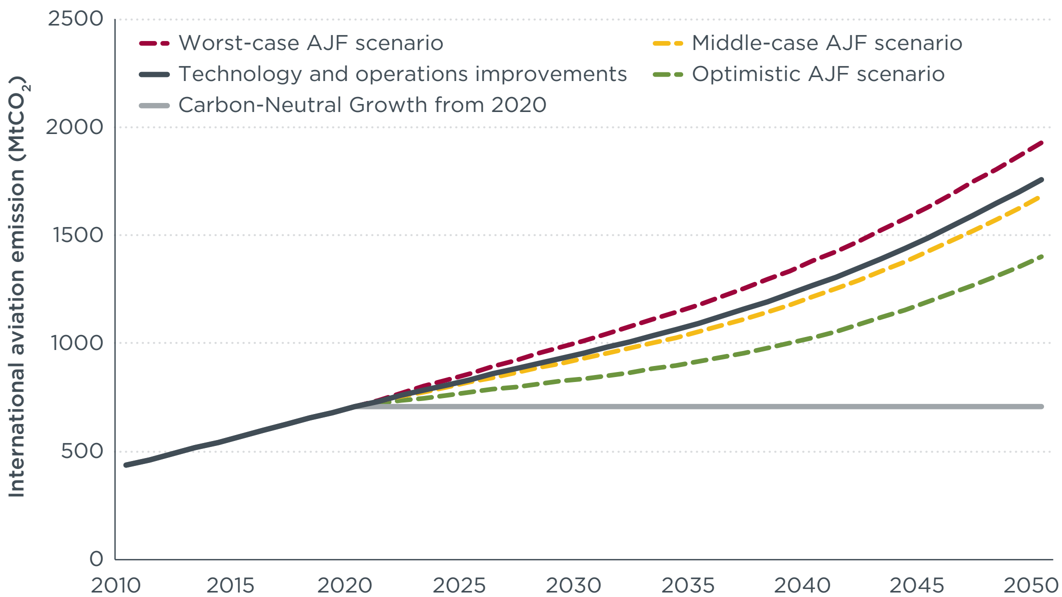

Figure A. Potential contribution of alternative jet fuels to GHG emission reductions in international aviation.
Note: Estimates of AJF emissions include technology and operations improvements.

A literature review on estimated production costs of AJF for all pathways and feedstocks reveals that they are not commercially competitive with petroleum-derived jet fuel, even when the costs are assessed for Nth-of-a-kind plants. Estimated production costs for AJF from lignocellulosic feedstocks range from 1,000–8,000 $/tonne, whereas conventional jet fuel costs on the order of 470–860 $/tonne. AJF from sugar and starch is estimated at 800–4,800 $/tonne. AJF from vegetable oil is more technologically mature, and costs are estimated at 1,000–2,000 $/tonne. Reported costs from actual purchased fuels are considerably higher, which is to be expected from first-of-a-kind biojet facilities.

Several commercial agreements and demonstration flights have occurred so far. However, two factors from the demand side seem to limit the large-scale commercialization of AJFs and are expected to limit their use in the future: the airlines' price sensitivity, and the lack of taxes on conventional jet fuels resulting in an overall lower willingness to pay from the aviation sector relative to competing sectors, such as road transport. On the supply side, producers of AJFs face barriers to commercialization similar to those of producers of advanced biofuels for the road transportation sector: political uncertainty and low investment.

The large-scale deployment of AJFs will likely be constrained to a large extent by the sustainable availability of feedstock in conjunction with the high costs of producing AJF. The fuels that could provide the greatest GHG reductions, such as wastes and residues, also tend to have the lowest availability and some of the highest conversion costs. Together, these factors could limit the commercialization progress of AJF and the contribution of fuel switching to the aviation sector's goal of achieving carbon-neutral growth from 2020 onward. Moving forward, it is imperative that ICAO includes a GHG-reduction threshold that addresses indirect effects for fuels to qualify for CORSIA. In practice, this would exclude feedstocks with substantial ILUC emissions, such as palm oil, which have a higher carbon intensity than the petroleum they would displace. Furthermore, a strict threshold would provide greater policy support for feedstocks and technologies with the greatest potential to contribute to the ambitious GHG-reduction goals under CORSIA. Without more clarification on which fuels qualify for CORSIA and how their carbon intensity is calculated within the agreement, the role of AJF in reducing emissions from civil aviation will largely depend on the extent to which the industry utilizes the feedstocks that offer the greatest life-cycle GHG benefits; it is imperative that the industry avoids using the AJF feedstocks that undermine the climate goals of the ICAO.

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INTRODUCTION

Over the past 2 decades, the international civil aviation sector[1] has expanded dramatically, and it is forecasted to increase by 4.3% annually for the next 20 years. Lower prices in conjunction with increased economic activity in China, Southeast Asia, and the Middle East are the key drivers for this growth (IEA, 2016). The number of jet aircraft in service and the total passenger kilometers flown are also expected to double in the next 20 years (ATAG, 2016). The massive growth of the international aviation sector could lead to a corresponding boom in aviation emissions if the sector does not adopt emissions-mitigation strategies.

Air travel currently accounts for only 2% of anthropogenic carbon dioxide (CO_2) emissions worldwide (ATAG, 2016), but its relative share of global emissions could expand as other sectors decarbonize while the aviation industry continues to expand. The contribution of jet fuel to the total energy consumption in transport is expected to increase from 11% to 14% in the next 20 years (EIA, 2016). More than 99% of airline emissions are generated by the combustion of fuel (Faaij & van Dijk, 2012), and the emissions from international aviation, which account for approximately 65% of global aviation fuel consumption, are expected to increase to 1.1–1.5 billion tonnes CO_2 by 2035 (ICAO, 2016b). Aircraft also emit other gases and particles that have climate impacts, such as water vapor, nitrogen oxides, sulfur oxides, and soot (IPCC, 1999).

The International Civil Aviation Organization (ICAO), a United Nations agency that works with 191 member states and industry groups to develop policies, standards, and recommended practices for the civil aviation sector, has begun to implement policies to address the climate change impacts of international aviation (ICAO, 2016a). Under the United Nations Framework Convention on Climate Change (UNFCCC), greenhouse gas (GHG) emissions from international aviation are not included in national GHG inventories or targets; therefore, these emissions are not regulated at a national level. Instead, the Kyoto Protocol to the UNFCCC specifies that industrialized countries shall pursue limitation or reduction of GHG emissions from aviation through the ICAO (UNFCCC, 1998).

To facilitate carbon-neutral growth of international civil aviation GHG emissions after 2020, ICAO introduced the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). CORSIA is a global market-based measure system to offset international aviation emissions growth if in-sector measures—technological improvements, operational efficiency measures, and alternative aviation fuels—are insufficient to cap emissions at 2020 levels. The remaining reductions would be met with offsets, such as emissions-reduction credits from the UNFCCC's Clean Development Mechanism (ICAO, 2016d).

ICAO's Committee on Aviation Environmental Protection assessed trends in aviation fuel consumption and CO_2 emissions (ICAO, 2016b) toward 2050, illustrated in Figure 1. The calculations estimate the CO_2 emissions associated with jet fuel combustion only, using an average emission factor of 3.16 kg CO_2 emitted per kg of fuel. The curve with the highest emissions represents the baseline fleet replacement scenario, based on

1 International civil aviation comprises civil aviation flights that depart in one country and arrive in a different country (ICAO, 2016d). International aviation represented 65% of global aviation fuel consumption in 2010 and is expected to reach 70% by 2050 (ICAO, 2016b).

a compound average annual growth rate of 5.3% (2010 to 2030), and assuming that no technological or operational improvement takes place.[2] The colored slivers cover different scenarios combining ICAO's low to optimistic estimates for the evolution of technological and operational improvements. The projections illustrate different strategies to mitigate emissions and achieve carbon-neutral growth from 2020.

» **Technology improvements:** This is the range of estimated emission reductions due to aircraft technology improvements. Such improvements are driven by international standards developed by ICAO, in addition to competition and fuel prices. For example, in February 2016, ICAO finalized a proposed performance standard for new aircraft that will impose binding improvements in fuel efficiency and reductions in CO_2 emissions (ICAO, 2016c). The standards will require, on average, a 4% reduction in the cruise fuel consumption of new aircraft starting in 2028 compared to 2015 deliveries, with the actual reductions ranging from 0 to 11%, depending on the maximum takeoff mass of the aircraft (Rutherford & Kharina, 2016). This compares to research suggesting that the average fuel burn of new aircraft can be reduced by approximately 25% in 2024 and 40% in 2034 using emerging technologies (Kharina, Rutherford, & Zeinali, 2016).

» **Operations improvements:** This is the range of estimated emission reductions due to operational improvements, such as new communications, navigation, surveillance, and air traffic management systems. These measures permit more direct routings and the use of more efficient flight conditions, such as optimum altitude and speed. Other operational techniques to minimize fuel consumption are to maximize the aircraft's load factor or to minimize the empty mass of the aircraft (ICAO, 2004, 2013).

» **Alternative jet fuels:** This comprises emission reductions due to the substitution of petroleum-based jet fuels with alternative aviation fuels.

» **Market-based measures:** This includes a variety of strategies to reduce emissions through various flexible approaches, including levies on carbon, emissions trading, and offsetting. Under CORSIA, this mostly comprises emission reductions achieved through offsetting. Offsets represent a way for the emitters to invest in emission reductions elsewhere, and to count the achieved emission reductions, represented as offset certificates, as part of their contribution to emission reductions (ICAO, 2016b).

2 The range of uncertainties associated with this forecast is higher than the potential contributions from the considered improvements (ICAO, 2016b).

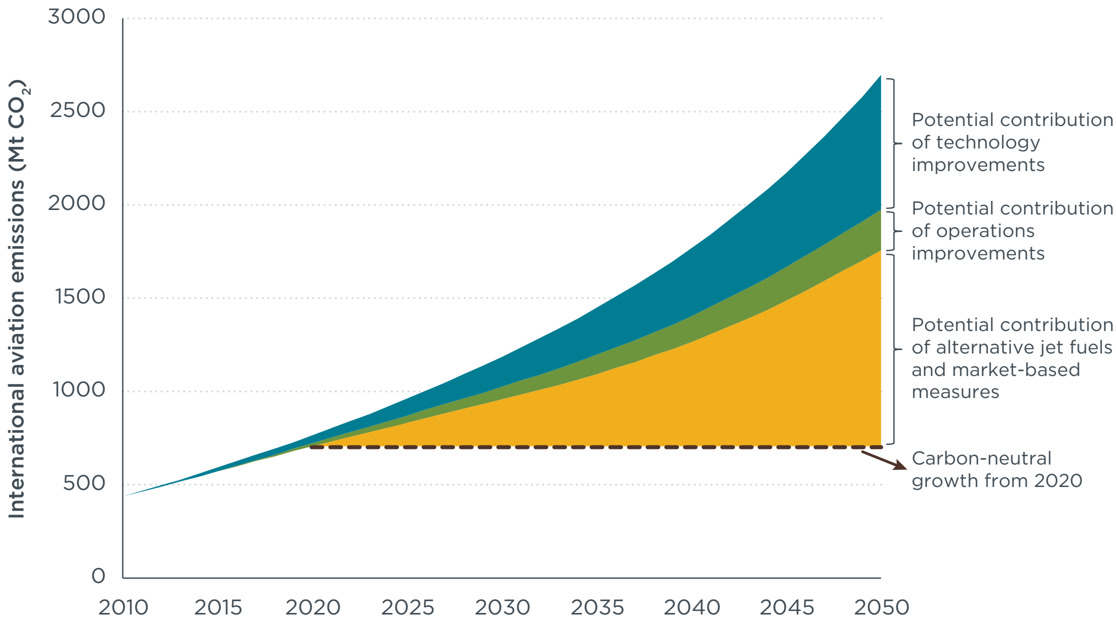

Figure 1. International civil aviation emissions and mitigation strategies. Adapted from ICAO (2015, 2016b).

Technological and operational improvements alone cannot reduce aviation emissions enough to meet ICAO's target of carbon-neutral growth. ICAO's findings indicate that before factoring in the contribution of carbon offsets, the bulk of the emissions reductions needed for international aviation would have to come from a transition to alternative aviation fuels. *Alternative aviation fuels* (or AJFs) generally refer to fuels made from non-conventional sources (conventional sources include fossil sources such as crude oil, natural gas liquid condensates, heavy oil, shale oil, and oil sands [ASTM, 2016a]). AJFs do not necessarily generate lower carbon emissions than conventional petroleum-based fuels. However, the contribution of AJFs to GHG mitigation rests on a variety of assumptions and is limited by two main considerations: the carbon intensity of AJFs and the availability of the feedstock that would be required to produce them in a sustainable manner.

This report explores the potential for AJFs to provide the necessary emission reductions for the international aviation sector. Our goal is to identify which feedstocks represent the most promising opportunities to deliver genuine environmental benefits, and which ones present potential risks. To do this, we first assess existing AJF production pathways and determine their carbon intensities relative to the baseline intensity of petroleum-derived jet fuel. From there, we evaluate the availability of feedstocks to produce AJF in the needed quantities; the current state of commercialization; and, lastly, the production costs for those fuels.

ALTERNATIVE JET FUEL PRODUCTION PATHWAYS

Although it is derived from petroleum, conventional jet fuel has different specifications from road fuels such as gasoline and diesel. AJFs must meet those specifications to be used commercially. Jet fuel is composed of a complex mixture of C_8–C_{17} hydrocarbons mainly produced from the kerosene or naphtha fraction of petroleum distillation, and its composition varies depending on crude source and manufacturing process (ASTM, 2016a; MathPro, 2011; Yan et al., 2013).

New AJFs must be certified to be qualified for commercial use in aviation. Standards have been developed to assess the suitability of synthesized hydrocarbons from non-conventional sources. One of the main regulatory bodies that set standards and specifications for aviation fuel for commercial purposes is ASTM International. ASTM Standard D7566 specifies technical requirements for AJF and blends with petroleum kerosene, such as heating value, fuel density, freezing point, fluidity, aromatic content, and thermal stability (ASTM, 2016b). For example, ASTM sets a minimum level of aromatics for AJF that prevents some fuels, such as synthesized paraffinic kerosene, from being used without blending (Lokesh, Sethi, Nikolaidis, Goodger, & Nalianda, 2015). Fuels complying with ASTM D7566 can be blended with conventional jet fuel in determined proportions and integrated into the existing supply infrastructure.

To meet these specifications, several production pathways to produce AJFs are available that use a range of feedstocks, through different biological, chemical, mechanical, and thermal processes. Figure 2 provides an overview of the major routes to AJF. This is not an exhaustive picture of all the existing pathways; several other pathways are being explored to produce AJF. The processes occur in different stages of development, from the research and development stage to the pre-commercial and commercial stages.

To date, five different AJF products have been qualified for blending with petroleum jet fuels by ASTM D7566 (the maximum percentage of blended volume for each approved AJF is here indicated in parenthesis): hydroprocessed esters and fatty acids (50% blend), Fischer-Tropsch kerosene without and with aromatics (both 50% blend), synthesized iso-paraffins from hydroprocessed fermented sugars (10% blend), and alcohol to jet kerosene (30% blend; ASTM, 2016b).

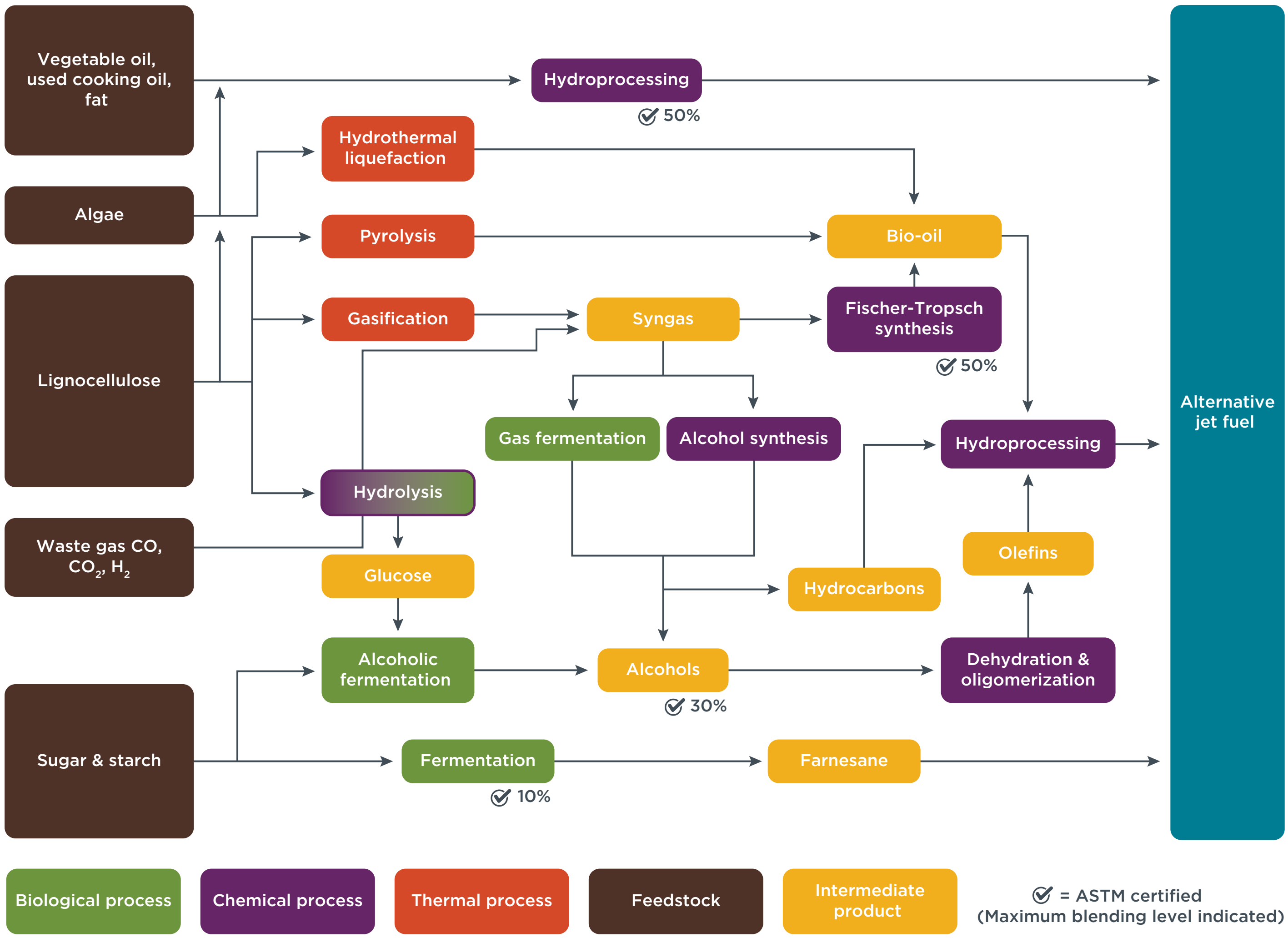

Figure 2. Selected pathways for alternative jet fuel production. Adapted from Brooks et al. (2016); Chuck (2016b); FAPESP, Boeing, Embraer, & UNICAMP (2013); Lorne (2016); Mawhood, Cobas, & Slade (2014); and Sizmann, Roth, & Jeßberger (2016).

It is possible to classify pathways into broader groups according to the type of feedstocks or technology used. Here we use the following classification into three major groups of pathways: lipid conversion, thermochemical conversion, and biochemical conversion (Cortez et al., 2014, 2016). Some pathways are hybrid and combine different types of conversions (e.g., gasification [thermochemical conversion] followed by syngas fermentation to ethanol [biochemical conversion]).

LIPID CONVERSION PATHWAYS

Hydroprocessed esters and fatty acids (HEFAs), also known as *hydrogenated vegetable oils*, are produced by the conversion of vegetable oils or waste oils and fats into diesel or jet fuel. HEFA fuels are chemically different than biodiesel produced by transesterification of oils (fatty acid methyl esters), and they show reduced nitrogen oxide (NO_x) emission, better storage stability, and better cold properties (Furimsky, 2013).

The first step to produce HEFA is hydrogenation, where the oils or fats are saturated with hydrogen. The saturated triglycerides are then converted into free fatty acids, which are converted in alkanes and treated by hydroprocessing to create shorter and branched hydrocarbons. A fractionation process then separates the resulting mixture to diesel, naphtha, light gases, and jet fuel (Han, Elgowainy, Cai, & Wang, 2013; Wang and Tao, 2016). The resulting HEFA jet fuel is called *hydroprocessed renewable jet*, or *synthetic (or synthesized) paraffinic kerosene* (SPK, or bio-SPK) and has carbon chains ranging from C_9 to C_{15}, depending on the fatty acid profile of the feedstock. It is chemically nearly equivalent to conventional jet fuel, and it can be blended in limited amount with conventional jet fuel.

HEFA technology is already relatively commercially mature; the process is commercially available and has been used in several military and commercial flights, at blends of up to 50% with conventional jet fuel (BioJetMap, 2016). Furthermore, diesel produced through the HEFA pathway is referred to as *renewable diesel* or *green diesel*. It has longer carbon chains than HEFA jet fuel and is being produced by about 10 plants worldwide, totaling a global production volume of 1.2 billion gallons in 2014 (EIA, 2016). HEFA diesel has lower production costs than HEFA jet fuel, and it is being studied as a blending component of jet fuel. In 2014, Boeing carried out a flight test with 15% renewable diesel (Neste, 2014).

THERMOCHEMICAL CONVERSION PATHWAYS

Thermochemical pathways utilize all the components of the biomass, including lipids, proteins, and carbohydrates, to generate a liquid product called *bio-oil*. They can be used to convert lignocellulosic feedstocks into jet fuel. Depending on the feedstock and process used to produce them, bio-oils will have different yields, physical properties, and chemical compositions (Furimsky, 2013). Bio-oils can contain up to several hundred compounds, including hydrocarbons and oxygenated compounds, resulting in high levels of oxygen, nitrogen, and sulfur (Raikova, Le, Wagner, Ting, & Chuck, 2016). Bio-oils must be upgraded before they can enter the conventional fuel stream, notably because of the presence of oxygenated organics, which are not suitable for engine applications (Zhang et al., 2015).

Biomass can be converted into bio-oils through three separate processes:

» **Fast pyrolysis:** Fast pyrolysis, also called *hydro-treated depolymerized cellulosic jet* or *hydrogenated pyrolysis oil*, refers to the rapid heating of dry biomass to temperatures of approximately 400°C–500°C in the absence of oxygen, causing decomposition of the biomass and resulting in the formation of bio-char, bio-gas, and bio-oil. Pyrolysis results in the formation of a bio-oil with high oxygen and water content (Furimsky, 2013).

» **Fischer-Tropsch synthesis:** In Fisher–Tropsch synthesis (F-T), also called *biomass-to-liquids*, the feedstocks are first gasified at high temperatures (700°C to 1,600°C) in the presence of a limited amount of oxygen and/or steam, to produce a mixture of carbon monoxide (CO), hydrogen gas (H_2), and CO_2, known as *synthesis gas* or *syngas*. The actual F-T process is the catalytic conversion of the syngas into bio-oil. Bio-oil is then upgraded, resulting in the formation of a jet fuel called *Fischer-Tropsch synthesized paraffinic kerosene* (FT-SPK), or, when the aromatics content is intentionally increased, *Fischer-Tropsch synthesized paraffinic kerosene plus aromatics* (FT-SPK/A or FT-SKA).

- **Hydrothermal liquefaction:** Hydrothermal liquefaction (HTL), also called *catalytic hydrothermolysis*, uses water at near-critical conditions (200°C to 374°C, and 5–28 MPa), with or without a catalyst, to break down biomass into bio-oil with low oxygen content, alongside an aqueous phase, a solid char, and a number of gaseous products (Peterson et al., 2008; Raikova et al., 2016). HTL can be applied to a wide range of feedstocks, such as algae, lignocellulosic feedstocks, and oils (Elliott, Hallen, & Schmidt, 2015; Ramirez, Brown, & Rainey, 2015), and it is suitable for wet feedstocks, unlike pyrolysis or F-T, which require dry feedstocks. This is one reason why HTL processing has received particular attention for microalgae feedstock, for which traditional biofuel production pathways, such as lipid extraction, require a drying step (Biller & Ross, 2016). HTL has not been commercially deployed, as a result of technical constraints and high capital cost estimates. Companies such as Virent are developing the technology with the aim to commercialize it (Cortright, 2015).

After undergoing these conversion processes, the resulting bio-oils are converted into AJF through a series of processes called hydroprocessing used in conventional petroleum refining. *Hydroprocessing* is a term that refers to two separate chemical engineering processes: hydrotreating and hydrocracking. Hydrotreating refers to a catalytic reaction with hydrogen to reduce impurities and generate a uniform product for further processing. Hydrocracking then further breaks down complex hydrocarbon molecules into simpler ones, with the aim to transform low-value heavy oil fractions into higher value products. Hydroprocessed bio-oils can be sent to fractionation, a process that separates the various fractions of hydrocarbons based on their differences in boiling point temperatures, including jet fuel, diesel, kerosene, gasoline, naphtha, and wax (Colorado School of Mines, 2016; Hsu, 2011; MathPro, 2011).

Although hydroprocessing results in the production of jet fuel together with other hydrocarbons, a producer can choose to produce more jet fuel by cracking the diesel range molecules to the jet range. It is even technically possible to convert all of the diesel fuel to lower molecular-weight products. However, the selectivity of the cracking reaction is difficult to control, and the economic margins to produce diesel is greater than for jet fuel (E4tech, 2014; Pearlson, Wollersheim, & Hileman, 2013).

Power-to-liquids

Power-to-liquids (PtL) is a pathway that produces hydrocarbons from electricity, water, and CO_2. It consists of three main steps: hydrogen production (e.g., from the electrolysis of water), CO_2 supply, and synthesis of hydrocarbons through Fischer-Tropsch or methanol synthesis. The individual process steps of the PtL pathway are at an advanced technological maturity; some are already being used at large-scale refineries. However, an integrated PtL process chain for the production of jet fuel has yet to be demonstrated. CO_2 can be extracted from concentrated sources, such as exhaust gases, using established industrial-scale processes. Processes for the extraction of CO_2 from air are still at a demonstration level maturity (Schmidt, Weindorf, Roth, Batteiger, & Riegel, 2016).

BIOCHEMICAL CONVERSION PATHWAYS

Alcohol to jet

The alcohol-to-jet (ATJ) pathway includes several technologies that convert a variety of alcohols (C_2 to C_6) and oxygenated compounds to SPK jet fuel. For example, ethanol can be converted to jet fuel through the production of different intermediates, such as ethylene. The ATJ pathway involves dehydration of the alcohol, and oligomerization of the resulting intermediate to longer hydrocarbon chains. The products are then hydrotreated and fractionated to produce jet fuel. ATJ technologies are being developed by several companies, such as LanzaTech, UOP, and Gevo (Brooks et al., 2016).

ATJ can use different types of feedstock. The alcohols can be produced from sugar or starch-containing feedstock through biological alcoholic fermentation. Alternatively, waste flue gas (CO, CO_2, and H_2 from steel mills or processing plants) or syngas produced by the gasification of lignocellulosic biomass can be fermented to alcohols by specialized microorganisms (Liew et al., 2016).

Direct sugar to hydrocarbons

Direct sugar to hydrocarbons (DSHC), also referred to as *synthesized iso-paraffins produced from hydroprocessed fermented sugars* (SIP), *fermentation to jet* or *direct fermentation of sugar to jet*, is a pathway where sugars are fermented and then hydroprocessed into a synthetic jet fuel. Instead of ethanol, genetically engineered microorganisms ferment sugars to produce farnesene. Farnesene then reacts with hydrogen to produce farnesane, a C_{15} alkane. Farnesane is purified by distillation to produce synthetic jet fuel (Zschocke & Scheuermann, 2015). Farnesane is the only SIP approved in ASTM D7566 (ASTM, 2016b); however, it is expected that other products will be included in this pathway in future versions of the standard (Dorrington, 2016). SIP is currently produced from sugary feedstocks, although it potentially could be produced from cellulose. The benefits to produce SIP from cellulosic feedstock would be likely much higher than from foods, due to reduced risk of indirect effects and lower upstream inputs. However, the complexity of fermenting cellulosic feedstocks means that they are not the focus of current research efforts (Mawhood et al., 2014).

GHG PERFORMANCE

The potential emission reductions from using AJF correspond to the life-cycle GHG emissions of the specific AJF in question. The carbon intensity of a given fuel is estimated using life-cycle assessment (LCA) methodology and is typically expressed in gCO_2 equivalent per MJ of fuel (i.e., its carbon intensity). This metric includes the GHG emissions and sequestration from feedstock production, collection and transport, and fuel production and transport through its final use. The net total impact of all of these life-cycle phases is commonly referred to as the *well-to-wake* (WTWa) or *cradle-to-grave emissions*. The emissions-reduction potential of a given fuel is therefore derived by subtracting the carbon intensity of AJF from the baseline carbon intensity of petroleum-derived jet fuel. An alternative fuel that offers minimal or non-existent GHG reductions should not be considered a viable means of reducing international aviation emissions to meet ICAO's climate-change-mitigation goals.

LCAs typically include some combination of direct and indirect elements. Direct emissions are those attributable to the historical footprint of a manufacturing process (e.g., refinery emissions for crude oil), whereas indirect elements include market-mediated behavioral responses on a macro scale (e.g., shifts in land use in response to a biofuel mandate). These elements are then harmonized on a per-unit basis for the product in question (i.e., the functional unit). LCAs require methodological choices that can widely differ between different sources, and this can affect the reliability and comparability of the results of an assessment (Wolf, Pant, Chomkhamsri, Sala, & Pennington, 2012).

AJF derived from biomass can cause both direct and indirect emissions due to LUC. LUC refers to sources and sinks associated with GHG emissions from human activities that change the way land is used or affect the amount of biomass in existing biomass stocks (Watson et al., 2010). Direct land use change occurs when land is converted to grow feedstock for bioenergy, causing a shift in that land's carbon stocks due to changes in management practices.

Indirect land use change (ILUC) is an indirect effect attributable to biofuel policies, occurring in response to increased demand for biomass. ILUC considers the change in emissions from land conversion for land that is not directly used to grow the feedstock in question. Emissions attributable to ILUC can occur when existing cropland is diverted to meet the increased feedstock demand of additional biofuel production, resulting in the displacement of other agricultural production activities onto land with high carbon stocks or other ecosystem services (Malins, Searle, & Baral, 2014). Although ILUC cannot be directly measured or observed, the GHG emissions associated with ILUC can be assessed through models. For example, Valin et al. (2015) quantified LUC[3] emissions and concluded that the conventional ethanol feedstocks (sugar and starch) perform better than vegetable oils. The study found that peat land drainage for oil palm plantation expansion plays a large role in LUC emission values for palm oil and other vegetable oils. Valin et al. (2015) estimated that biofuels made from energy crops (e.g., short rotation woody biomass and perennials) have negative LUC emissions, due to the increase in the carbon stock on the land that is converted and low pressure on international land use.

3 The LUC emission values are in fact the sum of direct and indirect emission effects, because the modeling does not show to what extent the land conversion is caused directly or indirectly (Valin et al., 2015).

Several GHG intensities for AJF specifically are published in the literature, covering various pathways and feedstocks. Figure 3 presents values taken from the literature and aggregated per main type of feedstock and technology. The dotted lines correspond to high and low estimates of GHG intensities of petroleum-derived jet fuel, with reported values between 88 and 106 g CO_2e/MJ (Capaz & Seabra, 2016; Lokesh et al., 2015). Filled points are WTWa emissions without LUC, and unfilled points include LUC, either as provided in the published estimates, or as WTWa values to which are added LUC factors calculated by Valin et al. (2015). Valin et al. (2015) calculated LUC emission values through the use of the GLOBIOM (Global Biosphere Management Model) for several types of feedstock, based on an increase in the European Union (EU) biofuels consumption. LUC emission values would likely be different for other regions of the world; hence, the values provided here are only indicative of responses to biofuel demand from the EU.

Figure 3 indicates that carbon intensities of some feedstock/pathway combinations exhibit considerable variation, in part due to variation in the carbon intensity of different conversion pathways and feedstocks, but also from the different methodologies used in the studies. This makes comparisons difficult and reflects the need for harmonization of LCAs in order to present a clearer picture of the GHG impacts of AJF.

All of the reported values for jet fuel produced from waste gas and from lignocellulosic feedstocks (included here are corn stover, forest residue, and switchgrass) are below the GHG intensities of conventional jet fuel, even when LUC is taken into account. For Fischer-Tropsch fuel from switchgrass, two values are negative and reflect the accumulation of carbon into soils and crops. For jet fuel from waste gas, large carbon credits are attributed to net gas absorption during the ethanol production stage, because the waste gases contain carbon that was prevented from release to the atmosphere (Brooks et al., 2016).

Few values can be found for the conventional ethanol feedstocks (sugar and starch) to jet. The ATJ and DSHC pathways are less carbon intensive than conventional jet fuel, except for one estimate of corn grain ATJ that includes LUC.

The vegetable oil and fat pathways display a considerable variability. All of the values for vegetable oils correspond to the HEFA pathway, and this is the pathway that has been the most studied due to the maturity level of the technology. The reported values for used cooking oil and tallow are all below conventional jet fuel. The other feedstocks (camelina, jatropha, palm, rapeseed, and soybean) are generally less carbon intensive than conventional jet on a WTWa basis when LUC is not considered. When LUC is included, the values range from low to very high, depending on the type of land conversion. For example, peatland oxidation and tropical forest conversions to palm plantations or soybean fields, such as those in Indonesia, have been estimated to cause GHG emissions exceeding 600 gCO_2e/MJ (Capaz & Seabra, 2016; Stratton, Wong, & Hileman, 2010). Microalgae-based jet fuels show a wide variation of carbon intensities, due to the different possible methodological configurations and cultivation conditions.

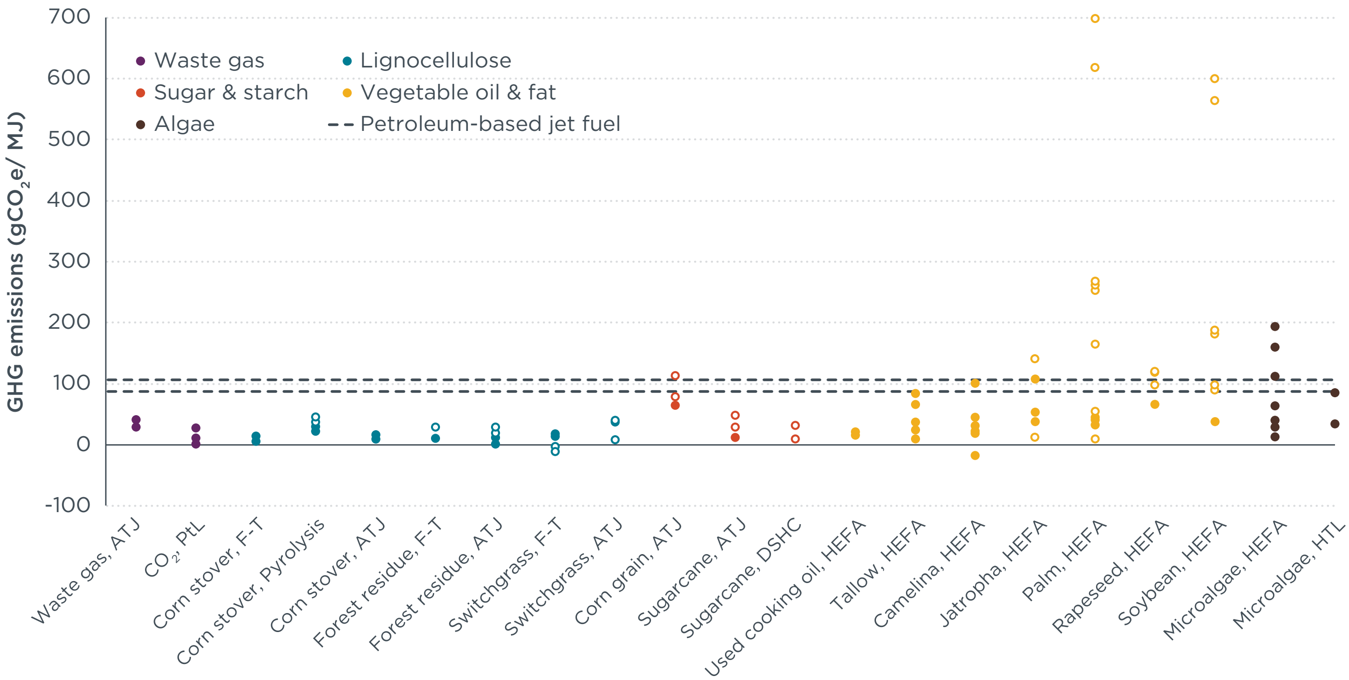

Figure 3. Carbon intensities of alternative jet fuels, grouped by category of feedstock and production pathway. Unfilled dots include land-use change estimates (ATJ = alcohol to jet, DSHC = direct sugar to hydrocarbons, F-T: Fischer-Tropsch, HEFA = hydroprocessed esters and fatty acids, HTL = hydrothermal liquefaction, PtL = power-to-liquids). Source data from Brooks et al. (2016); Capaz & Seabra (2016); Han et al. (2013); Holmgren (2009); Lokesh et al. (2015); Stratton et al. (2010); Warshay, Pan, & Sgouridis (2010); and Wong (2008).

According to some sources, life-cycle GHG emissions from alternative fuels can be up to 80% lower than traditional fossil jet fuel emissions (ATAG, 2016; IATA, 2016a; ICAO, 2016b). Considering the values reported in the literature, this percentage often cited by the aviation industry probably represents a relatively small share of the overall selection of feedstocks and pathways. We find that carbon intensities tend to be lower for biofuels made from lignocellulosic feedstocks, waste oil, waste gas, and sugar and starch, although the data for the last two feedstock categories are still scarce. Vegetable oil–based feedstocks and microalgae feature a wide range of variation among the studies, in particular for the conversion of vegetable oil (palm and soybean), which can be several times more GHG intensive than conventional jet fuel when LUC effects are taken into consideration. There are risks and opportunities associated with AJF in terms of GHG impacts, and this is highly dependent on feedstock choices. The promotion of pathways using feedstocks with a marginal improvement over conventional jet fuel would result in low GHG savings. If the aviation sector promotes the use of feedstocks with higher emissions than conventional jet fuel, the result would undermine the decarbonization goals of the sector.

SUSTAINABILITY CERTIFICATION

The GHG balance of a biofuel pathway is a critical metric in determining its overall environmental performance. Direct GHG emissions along with other key environmental factors of biofuel feedstock production, including land conversion, biodiversity, water consumption, and pollution, as well as socioeconomic impacts can be measured and verified, to some extent, by sustainability certification bodies.

Some stakeholders are considering the implementation of a global standard for the certification of sustainable AJF on environmental and social aspects (e.g., Alberici & Spöttle, 2016; Alberici, Spöttle, & Toop, 2014). Cases where sustainability certification is required for alternative fuels are typically based on requirements to meet certain sustainability criteria. For example, the EU Renewable Energy Directive (RED; European Parliament and Council, 2009) established sustainability criteria that eligible biofuels not be grown on land with high carbon stocks or biodiversity. Sustainability certification bodies verify that these criteria are met for a particular biofuel producer.

Sustainability certification, if sufficiently stringent, can be an important safeguard for the effectiveness of an alternative fuel policy, ensuring that the incentive does not unintentionally drive environmental harm. Certification schemes are independently operated and differ in their requirements and in how strictly they are implemented. For example, in a study that compared certification schemes approved to comply with the EU RED requirements, WWF Germany (2013) found that the schemes have very diverse performance with respect to environmental and social criteria. WWF also estimated that many schemes do not provide sufficient credible sustainable environmental and social standards and that some important issues are poorly represented in the approved schemes.[4]

In addition, certification schemes generally do not cover the impact of ILUC and thus may certify biofuel feedstock that is associated with high indirect emissions (European Court of Auditors, 2016). The Roundtable on Sustainable Biomaterials (2015) is the only scheme that contains criteria to address indirect impacts, but the effectiveness of such criteria to mitigate ILUC is questionable. A particular concern is that it lacks requirements to demonstrate that feedstock production or use is additional to what would have happened in a baseline scenario without biofuel demand (El Takriti, Malins, & Searle, 2016).

4 The report cites issues such as “the implementation of social and environmental management systems on the corporate level, handling of invasive species, limitations on the use of hazardous chemicals, waste and water management, restoration of riparian areas and segregation of supply chains in order to offer a non-GMO option.” The report also states: “many standards do not adequately address transparency in public reporting, internal system governance, and audit scope and intensity” (WWF Germany, 2013).

BIOMASS AVAILABILITY

The potential supply of low-carbon feedstocks is constrained, and their availability may be low relative to the scale envisioned by the aviation industry. Consequently, the ability of the aviation sector to meet AJF production and GHG reduction targets depends on the amount of sustainable feedstock that will be available for the sector.

In general, the potential to use feedstock for aviation fuel will be limited by the competing uses from other sectors for the same resources. Power generation (heat and electricity), biochemical, and transportation sectors all have their benefits and drawbacks when one tries to compare which sector offers the best environmental or economic performance (Pavlenko, El Takriti, Malins, & Searle, 2016). In the EU, biomass is considered as having an important role toward the cross-sector decarbonization of the economy up to 2050 (European Commission, 2011).

Waste and residues constitute a sustainable feedstock among the pool of options for bioenergy production, when the displacement impacts from existing uses are taken into consideration (Allen, Baldock, Nanni, & Bowyer, 2016). In the case of biogenic waste, agricultural residues and forestry residues, only limited amounts of feedstock can be harvested without undue adverse impacts on the environment—in particular, soil quality—or on existing uses from other industries (Searle & Malins, 2016). Energy crops also represent a potential candidate when they are grown on land that can be converted with minimal environmental costs (unused or underutilized land with low productivity, low carbon stocks, and low biodiversity; Searle, Petrenko, Baz, & Malins, 2016). Food-based feedstocks are more problematic—in particular, vegetable oils—because they are associated with indirect emissions, as discussed below. Sugar and starch-based feedstocks are also associated with indirect emissions, although generally on a smaller scale than vegetable oils (Valin et al., 2015).[5]

Non-food fats and oils also present an option for AJF. Used cooking oil (UCO) is a feedstock associated with a low environmental impact, but its supply is relatively inflexible and has many existing uses. For example, in the EU, around 700,000 tonnes of UCO are currently collected—from the professional sector and from households—and used per year, but this resource is unlikely to increase more than an additional 300,000 tonnes per year in the EU, even with strong government support for improved household UCO collection systems (Hillairet, Allemandou, & Golab, 2016). This amount of resource could result in the production of a modest amount of AJF in the EU through the HEFA pathway, but that resource is limited overall, and there are competing demands from the road transport sector. Because of current biofuel policies in the EU and the United States, it can reasonably be expected that a significant proportion of that feedstock will be used to produce biodiesel for the road sector in the foreseeable future.

Lignocellulosic biomass can offer substantial GHG reductions as an AJF feedstock. However, its supply is also eventually limited by global land area. Searle & Malins (2014) estimated that the maximum plausible limit to global biomass availability in 2050 is 60–120 EJ/year in primary energy from energy crops, forestry, crop residues, and wastes. This amount of biomass could only be produced in a drastic scenario that allows for the conversion of virtually all unused grassland and savannah, and it

5 See GHG Performance section for more detail.

would result in extensive LUC and biodiversity loss. It is furthermore unlikely to be realized, because it would require political commitment across the globe to expand bioenergy production. After accounting for competition from electricity and heat and conversion losses, the authors estimated that maximum potentials of 10–20 EJ/year of biofuel would be available in 2050. Given the additional costs associated with producing AJF relative to road biofuel, it is likely that most biomass used in the transport sector would be consumed in road vehicles.

Figure 4 develops the biomass availability projections from Searle & Malins (2014) to estimate the emissions impact of allocating various shares of the biomass to aviation. Assuming that 25% of global biofuel could be available for use in the aviation sector by 2050, the absolute maximum amount of cellulosic AJF would be around 4 EJ/year, representing 18% of ICAO's estimated total jet fuel consumption for international aviation.[6] For this maximum bioenergy scenario, we can estimate an emissions reduction of around 357 million tonnes CO_2e per year; this represents the maximum possible GHG benefit that could be achieved through AJFs in 2050 (indicated by the green dotted line in Figure 4).

In a more realistic scenario wherein global bioenergy production does not reach its limit and the relative shares allocated to transport and aviation are between the optimistic scenario and what is used today, around 1.1 EJ/year AJF could be available, leading to around 80 million tonnes CO_2e reduction annually in 2050 (yellow dotted line in Figure 4). We also consider a worst-case scenario, in which AJF production achieves the level in the optimistic scenario, but is produced mainly from food-based feedstocks with worse GHG performance. In this scenario, 4.6 EJ/year of AJF would cause a net increase in emissions of around 170 million tonnes CO_2e/year in 2050 (red dotted line in Figure 4).[7]

6 ICAO's estimated total jet fuel consumption amounts to 24 EJ in 2050 for the most optimistic scenario (i.e., including operational and technological improvements).

7 Assumptions in these scenarios: The optimistic scenario follows Searle & Malins (2014) in total bioenergy production and assumes that 25% of transport biofuel is used in the aviation sector with a 56% energy efficiency of conversion. Carbon intensities range from 5–20 gCO_2e/MJ for lignocellulosic pathways, and the carbon intensity of conventional jet fuel is 88 gCO_2e/MJ. In the middle scenario, 75% of global cellulosic biomass potential is achieved, with 20% used in transport and 15% of that in aviation, with a 46% energy efficiency of conversion (based on today's conversion efficiency of 0.26 J jet fuel per J feedstock through Fischer-Tropsch [Diederichs, Mandegari, Farzad, & Görgens, 2016]). Approximately 0.06 EJ of waste oil is used. Carbon intensities range from 10 to 29 gCO_2e/MJ. In the worst-case scenario, 50% of global cellulosic biomass potential is achieved, with 5% used in transport, 5% of that used in aviation, and a 36% energy efficiency of conversion. Approximately 2.5 and 2 EJ of sugar/starch and vegetable oil AJF is produced, respectively. Approximately 0.02 EJ of waste oil is used. Carbon intensities range from 30–50 gCO_2e/MJ for lignocellulosic pathways, 75 gCO_2e/MJ for starch and sugar pathways, and 190 gCO_2e/MJ for vegetable oil pathways, roughly following Valin et al. (2015). AJF production was assumed to grow linearly from 2020 to 2050. For context, current global biofuel production is around 3.4 EJ/year, representing roughly 7% of global bioenergy consumption.

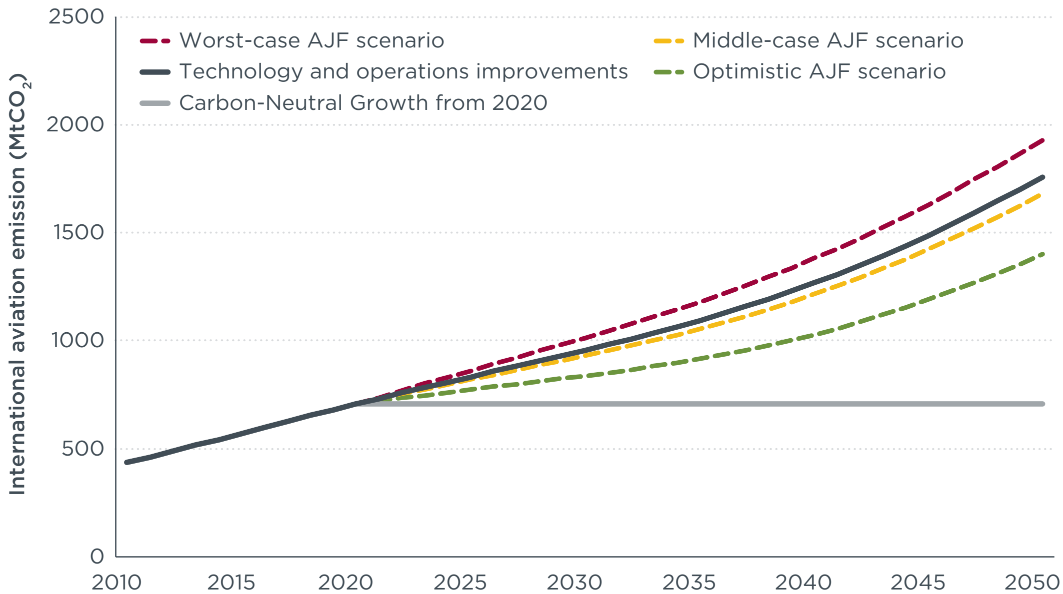

Figure 4. Potential contribution of alternative jet fuels to GHG emission reductions in international aviation. The three AJF scenarios include technology and operations improvements.

As another point of comparison, Figure 5 shows the projected global biofuel production according to a recent IEA projection (IEA, 2016) and the international aviation sector's fuel consumption to 2050 (ICAO, 2016b). According to the authors, the projections for biofuel production are based on a scenario that lays out an emissions trajectory[8] consistent with at least a 50% chance of limiting the average global temperature increase to 2°C (IEA, 2016). This scenario is based on a relatively stable production of conventional ethanol and a decrease in biodiesel production, resulting in a total production of 3.7 EJ in 2050 for total conventional biofuels. The scenario also assumes a rapid growth of advanced biofuels amounting to 13 EJ in 2050; this is consistent with the estimated range of 10–20 EJ/year of advanced biofuel in 2050 given as a maximum potential by Searle & Malins (2014) and thus should also be regarded as a very aggressive biofuel deployment scenario. The total amount of biofuels for road transportation reaches 17 EJ in 2050 in the IEA scenario. IEA also gives a projection for biojet fuel production that reaches 5 EJ in 2050; however, the type of feedstock that is assumed for production of that amount is not specified. Again, this is roughly consistent with the maximum possible amount of AJF that could be produced according to our scenarios above.

According to ICAO (2016b), one way of achieving carbon-neutral growth at 2020 emissions levels out to 2050 would be a nearly complete replacement of petroleum-based jet fuel with AJF in addition to implementing technological and operational improvements. The projections given in Figure 5 show that this is unrealistic, because it would require a minimum of 24 EJ/year just for the aviation sector, on top of all the biomass used to produce road biofuels.

8 IEA gives projections in 5-year intervals. For the purpose of drawing the lines in the chart, we assumed a linear growth between the values given by IEA.

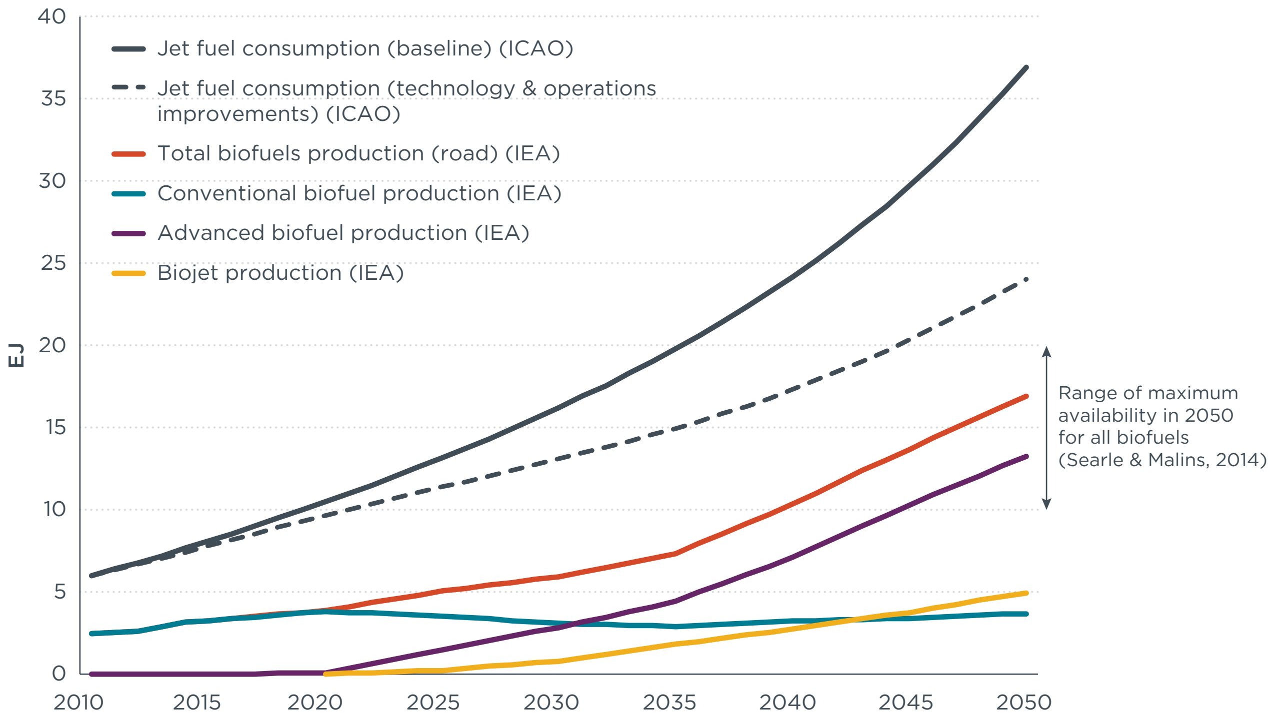

Figure 5. Estimated global biofuel production and jet fuel consumption from international aviation. Data from ICAO (2016b) and IEA (2016).

COST

The cost of AJF is not well known and involves a high degree of uncertainty. The process economics of AJF production is dependent on many variables, such as composition and cost of feedstock, conversion efficiency or product yield, co-product credits, plant size, process design, energy conservation, and degree of maturity of the technology (Milbrandt, Kinchin, & McCormick, 2013; Wang and Tao, 2016). Furthermore, public reporting of AJF production costs is almost inexistent as a result of commercial sensitivity.

Despite the uncertainty, a general trend can be observed based on the type of feedstock, as illustrated in Figure 6. Vegetable oils and fats require less processing than the other feedstocks (lignocellulose, sugar, and starch) because the molecules of triglycerides and fatty acids are more similar to the final hydrocarbons in jet fuel (Diederichs et al., 2016). Sugar and starch need to be fermented to intermediate products, and lignocellulose feedstocks require additional steps because they must be hydrolyzed to simpler sugars, or turned into intermediate syngas or bio-oil. Waste and residues (municipal solid waste and waste gas) require the highest processing because of the nature of the feedstocks and the complexity of processing involved. The cost of feedstocks follows an inverse trend: waste and residues are the cheapest, whereas vegetable oils and fats are the most expensive. Factoring in the results of the GHG performance analysis above, we see a similar trend here, with vegetable oils providing the lowest GHG savings and the GHG reductions increasing in conjunction with the technical efforts.

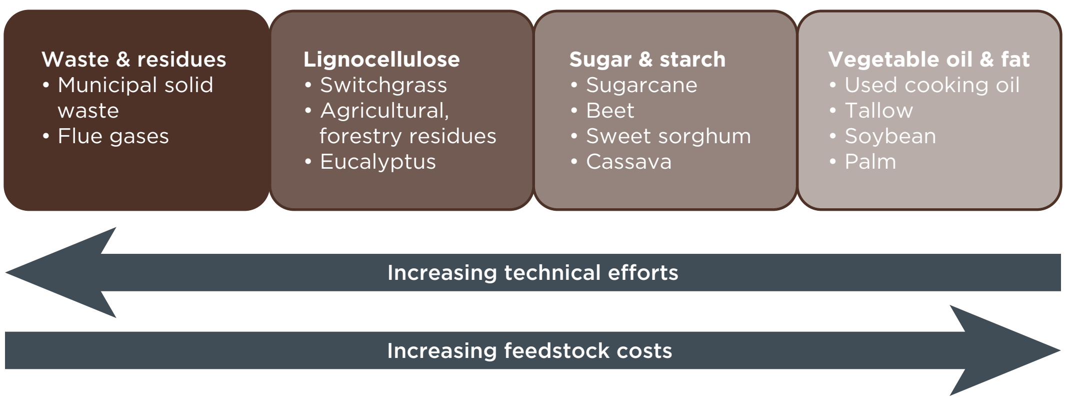

Figure 6. Feedstock costs and technical efforts. Adapted from Cortez et al. (2016).

Different production costs values are provided in the literature for different pathways. Figure 7 shows values for the production cost of AJF in $/tonne of fuel,[9] categorized by type of feedstock and pathway. Filled points indicate estimates for costs based on cost analyses and models, and unfilled points indicate actual costs reported in the literature. Most of the existing techno-economic analyses assess the conversion pathways that are certified under ASTM. The dotted lines represent, respectively, the bottom and top tenth percentile of petroleum-derived jet prices over the period 2005–2014, as reported in de Jong et al. (2015).

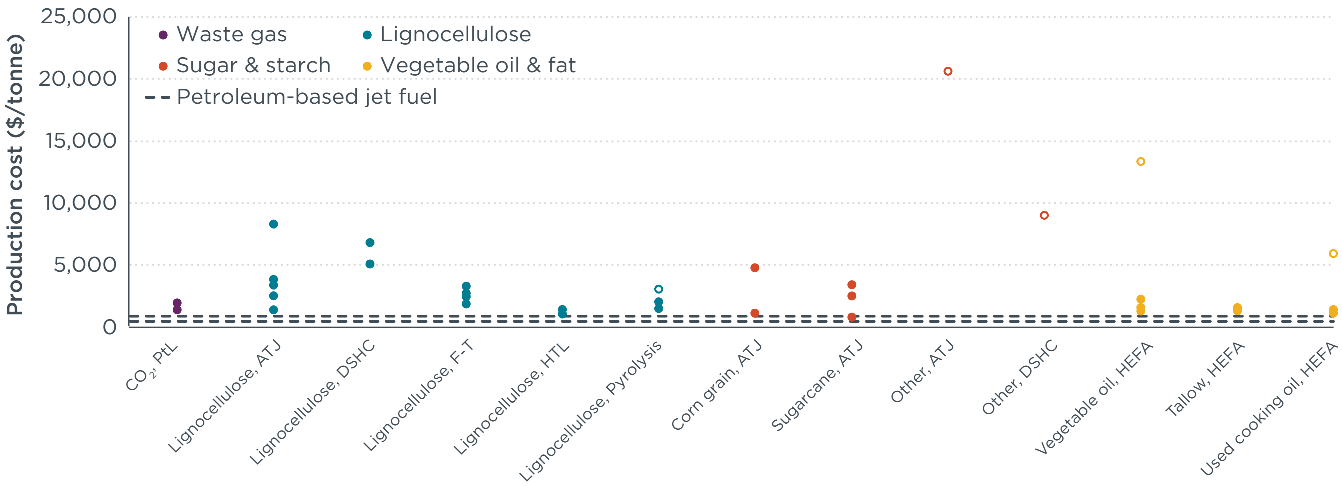

Figure 7. Theoretical (filled points) and actual (unfilled points) production costs of alternative jet fuels (ATJ = alcohol to jet, DSHC = direct sugar to hydrocarbons, F-T = Fischer-Tropsch, HEFA = hydroprocessed esters and fatty acids, HTL = hydrothermal liquefaction, PtL = power-to-liquids). Source data from de Jong et al. (2015); Diederichs et al. (2016); Gates (2011); IATA (2014); Pearlson et al. (2013); Schmidt et al. (2016); Staples et al. (2014).

Most of the actual costs (unfilled points in Figure 7) are from purchases made by the U.S. Department of Defense, as reported in IATA (2014). The actual costs are up to several times higher than the estimated costs. This is because analyses generally perform N^{th}-of-a-kind plant estimates, assuming a mature technology and production at a commercial scale. N^{th}-of-a-kind plant assessments generally assume lower capital cost and more favorable plant performance as compared to first-of-a-kind plants (de Jong et al., 2015). Even for the N^{th} plant estimates, the production costs for all pathways and feedstocks are not economically competitive with petroleum-derived jet fuel, whose highest production cost reaches 860 $/tonne ($2.5 per gallon). A notable exception is one estimate for the alcohol-to-jet pathway from sugarcane at 800 $/tonne ($2.3 per gallon).

Estimated production costs for AJF from lignocellulosic pathways display a range of values from 1,000 to 8,000 $/tonne. The estimates for the more technologically mature HEFA pathway are generally lower, around 1,000 and 2,000 $/tonne, although the actual costs are considerably higher. For the pathways based on sugar and starch, the estimates range from 800 to 4,800 $/tonne, and the actual costs are also much higher.

9 Production costs are reported in the literature per unit of energy, volume, or mass. In the present paper, all of the costs have been converted to dollar per unit of mass, using for all AJF a lower heating value of 44.1 MJ/kg and a density of 0.76 kg/L, as reported in the GREET® model (Wang, 2016) for synthesized paraffinic kerosene from F-T and HRJ pathways. The exchange rate €/$ was taken as an average value for 2015 (UKForex, 2016).

Several processes that generate jet fuel, such as HEFA, also produce co-products such as renewable diesel in varying proportions. These proportions can be tailored to increase or decrease the share of jet fuel. However, the profit margin for renewable diesel is generally greater than for jet fuel, thus reducing the incentive to configure plants for maximum jet fuel output (E4tech, 2014).

Jet fuel accounts for up to 40% of airlines' operating costs (Brooks et al., 2016). Therefore, the relatively high costs of production of AJF in conjunction with airlines' willingness to pay are important factors to take into consideration when assessing the potential development and use of AJF. Passing on higher fuel costs to customers may not be possible for airlines because of the competitive nature of the industry and the high price elasticity of the demand for air travel (Davidson, Newes, Schwab, & Vimmerstedt, 2014). Even though AJFs can offer a competitive marketing advantage for airlines using them, surveys and studies have shown that consumers are unwilling to pay higher prices for alternatives and that there is a disparity between consumer attitudes toward eco-friendly options and their behaviors (Brooks et al., 2016).

The price that AJFs would be able to command in the marketplace would likely be limited by the exemption of aviation fuels from taxation, meaning that buyers are typically used to paying lower prices than in other economic sectors. The 1944 Convention on International Civil Aviation establishes the legal framework for international civil aviation and requires all contracting states not to charge customs duty, inspection fees, or similar duties and charges on aviation fuel (ICAO, 2006).

The combined impact of airlines' price sensitivity in conjunction with the lack of taxes on conventional jet fuels result in an overall lower willingness to pay for costly AJF from the aviation sector relative to competing sectors, particularly the road sector, which generally is subject to higher taxation. The market costs for alternative fuels would need to be even lower in the aviation sector in order to be competitive—displacing a gallon of taxed road fuel costs more to potential buyers than replacing a gallon of jet fuel. This disparity suggests that the road sector may be able to support higher production costs for alternative fuels than the aviation sector. Consequently, the use of AJF must require favorable economics to become cost-competitive with fossil jet fuel; otherwise, consumption of limited supplies of feedstocks risks becoming crowded out by sectors willing to support higher costs.

COMMERCIALIZATION

Since the first commercial aircraft test flight on AJF in 2008, the use of AJF has expanded and interest has increased. Over the past several years, multiple airlines have used AJF in commercial flights and concluded offtake agreements with AJF suppliers. However, the commercialization of those fuels has remained limited because of a variety of factors, chiefly feedstock availability and cost.

IATA (2016a) reported that as of June 2016, 23 airlines have performed over 2,500 commercial passenger flights with blends of up to 50% AJF. Chuck (2016a) listed 1,568 commercial flights with blends of 15% to 50% AJF, as individual events or recurring operations between 2008 and 2013, totaling 0.6 million gallons of AJF. Notably, Lufthansa operated 1,187 flights with 50% blend HEFA produced by Neste Oil as part of a 6-month test run in 2011 (Neste, 2012; Zschocke, 2014).

Besides numerous commercial flights using AJF, several airlines have concluded long-term offtake agreements with AJF suppliers in recent years. IATA (2016b) reported 29 such agreements from 2009 to 2015. Some examples are provided in Table 1 and detailed below.

In 2014, the Hong Kong-based airline Cathay Pacific Airways made a strategic equity investment in Fulcrum BioEnergy and entered into a long-term supply agreement with the company for the delivery of AJF produced from municipal solid waste through F-T synthesis (Cathay Pacific, 2014; Fulcrum BioEnergy, n.d.). Cathay Pacific also started, in 2016, a 2-year program of flights from Toulouse to Hong Kong using Amyris's DSHC farnesane in 10% blends (Amyris, 2016).

In 2015, United Airlines announced a partnership with Fulcrum BioEnergy to produce AJF from municipal solid waste (United, n.d.). In 2016, United Airlines also started collaborating with AltAir Fuels and Honeywell UOP to operate commercial flights using AJF at a blend of 30%. AltAir Fuels retrofitted an existing idled conventional refinery in Paramount, California, into an AJF facility that converts waste oils and fats using the Honeywell Greenjet HEFA technology (Honeywell UOP, n.d.).

Table 1. Long-term offtake agreements between airlines and fuel suppliers. Adapted from IATA (2016a).

Airline	Fuel supplier	Volume (Mgallons/ year)	Feedstock	Technology	Duration	Expected first delivery
Cathay Pacific	Amyris/ Total	N/A	Sugar cane	DSHC (10% blend)	2 years	2016
United	AltAir Fuels	5	Waste oils and fats (tallow)	HEFA (30% blend)	3 years	2016
FedEx/ Southwest Airlines	Red Rock Biofuels	3	Forestry residues	F-T	7 years	2017
United	Fulcrum BioEnergy	90	Municipal solid waste	F-T	10 years	2018
Cathay Pacific	Fulcrum BioEnergy	38	Municipal solid waste	F-T	10 years	2019

Mawhood, Gazis, de Jong, Hoefnagels, and Slade (2016) conducted a review of commercialization status and future prospects for AJF. After researching peer-reviewed studies addressing the commercialization activities of AJF developers, the authors used a method called the "fuel readiness level"[10] to assess the progress of AJF technologies toward commercialization. The authors identified the HEFA and F-T pathways at the commercialization stage. Pyrolysis, DSHC, and ATJ are at the demonstration stage, and other pathways such as hydrothermal liquefaction are at a lower level (i.e., at the pilot or research and development stage).

E4tech (2014) and Hudson, Jefferson, Bauen, & Nattrass (2016) estimated that globally there are already planned and operational plants with a capacity of 1.8 million tonnes of AJF through various pathways and feedstocks. It is difficult to assess how realistic such estimates are, considering the possible overstating of commercial progress and production volumes capacities. In addition, such lists might include projects that did not go further than the announced planning, as was the case for the company KiOR that went bankrupt in 2014 (Biofuels Digest, 2016). Some plants listed as producing jet fuel are actually also producing other hydrocarbons like renewable diesel, such as ENI and Neste. However, such information can still provide an upper estimate on the quantity of present and forthcoming AJF production capacity. Assuming that all the plants reach the expected production volumes by 2020, 1.8 million tonnes of AJF would be produced (approximately 0.08 EJ). This represents 0.8% of the estimated jet fuel consumption of international aviation in 2020 (i.e., 10 EJ). Taking sustainability aspects of the feedstocks into consideration, the amount of AJF that could be produced sustainably would be much lower if feedstocks with high carbon intensity, such as oily crops, were excluded from such assessments.

Despite commercial flights and offtake agreements with AJF suppliers, the large-scale deployment of AJF is primarily limited by economic considerations. The cost-competitiveness of AJF must be taken into consideration when estimating its potential contribution to aviation fuel consumption. Previous studies on the second-generation biofuels industry have shown that the industry faces many barriers on the path to commercialization. Miller et al. (2013) have shown that investors would require a much higher expected annual rate of return for this type of industry than for others, and therefore they regard second-generation fuels as inherently riskier. This higher risk is one of the reasons that explain the unsteady and insufficient investment and the poor financial health of the advanced biofuels industry. Other risks include oil price volatility and political uncertainty, in particular the lack of regulatory climate to ensure long-term offtake, meaning that there is little certainty that produced fuels can be sold to the market at a sufficiently high price (Peters, Alberici, & Passmore, 2015).

The transition from research, development, and demonstration to commercialization, referred to as the "valley of death," has been the most difficult step in developing second-generation alternative fuel technologies, and only a few companies have been able to attract sufficient financing for commercial-scale facilities. The difficulties faced by advanced biofuels produced for road transportation are equally relevant for AJF, which may face a steeper path to commercialization.

10 The fuel readiness level was developed by the Commercial Aviation Alternative Fuels Initiative (CAAFI, 2010) and has been recommended by ICAO as a best practice tool to communicate fuel technology maturity and deployment (ICAO, 2009). The method comprises nine levels: 1–4 correspond to technological research and development, 5 to pilot, 6–7 to demonstration, and 8–9 to commercial deployment stages.

CONCLUSIONS

AJFs are promoted by the aviation industry as being an important measure toward achieving carbon-neutral growth from 2020. In reality, the large-scale deployment of AJF and the ability of the aviation sector to mitigate emissions through their use will be limited by several factors, mainly: the sustainability and availability of feedstock, the production cost, and the extent to which those fuels will be commercialized.

Some AJFs have the potential to deliver emission reductions compared to conventional jet fuel. In particular, fuels produced from lignocellulosic and waste feedstocks generally provide the highest reductions. Although the aviation industry reports GHG savings of up to 80% compared to conventional jet fuel, in reality, this percentage represents only a specific minority of feedstocks and pathways, and under certain methodological choices regarding how the LCA is carried out. Furthermore, AJF from oil-based feedstocks can be several times more GHG intensive than conventional jet fuel when LUC effects are taken into consideration.

Lignocellulosic feedstock and waste constitute a pool of sustainable feedstocks, but they have competing uses in non-transport sectors and the supply of wastes and residues is inelastic. Estimates for maximum availability of sustainable biomass (e.g., lignocellulosic feedstock) reveal that it would be impossible to substitute total jet fuel consumption with AJF up to 2050 or attain carbon-neutral growth through AJF only. Although estimated demand for jet fuel amounts to 24–37 EJ in 2050, assessments show that the absolute maximum amount of lignocellulosic biofuel that could be available for the aviation sector is around 4 EJ in 2050, resulting in emission reductions up to around 360 million tonnes CO_2. The actual amount of low carbon AJF that will be available is likely much lower.

Although the technology to produce AJF from lignocellulosic feedstock is at a relatively advanced stage, in particular Fischer-Tropsch synthesis, the most significant challenge to attain large-scale production is commercialization. Production costs of AJF reveal that they are not commercially competitive with petroleum-derived jet fuel. Estimated production costs for AJF from lignocellulosic pathways are valued at 1,000–8,000 $/tonne, whereas conventional jet fuel costs approximately 470–860 $/tonne. Furthermore, the airlines' price sensitivity relative to the road sector presents a possible disparity in terms of the aviation industry's ability to support production costs as high as competing sectors.

The aviation sector has the opportunity to deliver some GHG savings through the use of AJF, but it is unlikely that AJF alone can meet the bulk of the GHG reductions projected by the aviation industry due to feedstock supply and cost constraints. We recommend that ICAO stipulate a GHG reduction threshold in order for a given AJF to qualify under CORSIA, and includes indirect emissions in its life-cycle accounting. This would help to incentivize only the fuels that offer genuine GHG reductions, thereby avoiding the mistakes made by some initial alternative fuel policies within the road sector. Without strict criteria limiting the carbon intensity of qualifying fuels, the aviation sector could unwittingly invest in the cheapest AJFs that do not necessarily offer carbon reductions, potentially undermining the CORSIA scheme.

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