

# Policy and Environmental Implications of Using HEFA+ for Aviation

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## Introduction

The aviation sector must confront rapidly increasing greenhouse gas (GHG) emissions and ambitious decarbonization targets. The International Civil Aviation Organization (ICAO), the United Nations agency charged with coordinating international standards for civil aviation, projects that the greatest share of in-sector GHG reductions from aviation will come from transitioning away from petroleum-based jet fuel toward sustainable, low-carbon alternative jet fuels (AJFs). The AJFs that may replace petroleum in the future can vary widely in feedstocks used, cost, and environmental performance. These factors must all be taken into consideration when developing fuels policies for the aviation sector if its carbon emissions are to be successfully reduced.

To facilitate the transition to AJF, Boeing has begun testing the technical suitability of HEFA+ (Hydroprocessed Esters and Fatty Acids+) on flights as a petroleum jet fuel substitute. HEFA+, commonly called “green diesel” or high-freeze-point HEFA (HfP-HEFA),

is a synthetic hydrocarbon typically made from bio-feedstocks such as vegetable oil or waste fats. HEFA+'s primary competitive advantage stems from its similarity to renewable diesel [also known as hydrogenated vegetable oil (HVO) or hydrogenation-derived renewable diesel (HDRD)], a biofuel already produced at commercial scale for the road sector. Existing production of renewable diesel for the road sector dwarfs the scale of production of other potential jet fuel substitutes; production could theoretically ramp up quickly at existing facilities. If HEFA+ were to be certified as an AJF, it would therefore immediately have a market advantage relative to other AJFs that are further from commercialization. Proponents of HEFA+, such as Neste Corporation, tout the high technological readiness and relatively low price of HEFA+ relative to other AJFs; this suggests that, once certified, substantial volumes of HEFA+ could be used in the aviation sector in the near term (Erämetsä, 2017).

This study assesses the state of HEFA+ deployment within the aviation sector and its potential to reduce the climate

impacts of aviation. We first evaluate the production of HEFA+ and the impact of feedstock choice on HEFA+'s sustainability and GHG performance. The next section analyzes the state of HEFA+'s deployment and estimates the near-term availability of HEFA+. The final section discusses the policy implications of expanding HEFA+ use in the aviation sector and competition for feedstocks with the road sector.

## Production and Processing

HEFA+ production resembles the production of renewable diesel for the road sector, a process wherein vegetable oils, waste oils, and fats are processed into hydrocarbons. Renewable diesels chemically different from traditional biodiesels produced for the road sector, which are produced via trans-esterification to generate fatty acid methyl esters (FAME). FAME-based biodiesels may cause problems in some engines at high concentrations and thus require blend limits in the road sector; they cannot be used in aviation because of substantial chemical differences from petroleum-based jet

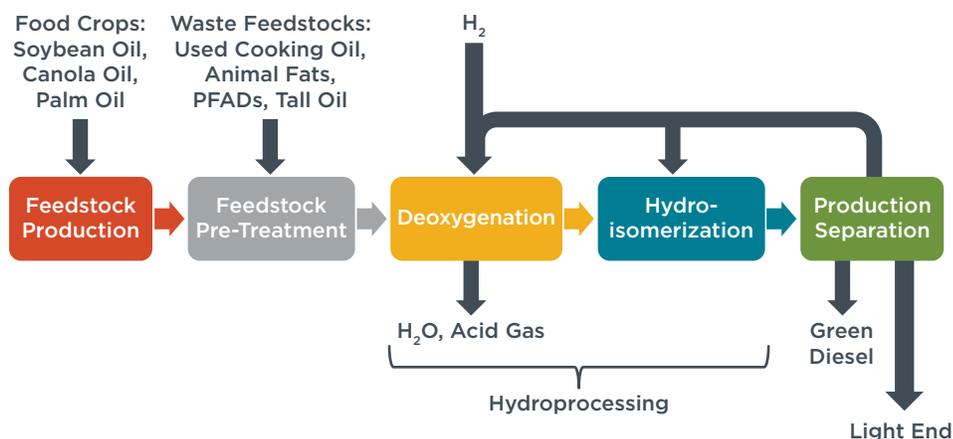
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fuel (Zeman, 2010). In contrast, the renewable diesel production process converts bio-oils into a chemical form more similar to fossil fuels, thus facilitating higher blending with petroleum-based diesel. The first step in renewable diesel production (Figure 1) is bio-oil treatment with hydrogen gas and a catalyst in order to remove oxygen (i.e., hydrotreatment). Once the oxygen is removed, the remaining hydrocarbon chains are then hydroisomerized to break down the long chains and improve the cold flow properties of the finished fuel. The end product generally contains hydrocarbon lengths in the diesel range, although further hydroisomerization can break down the chains of carbon even further, thereby increasing the share of bio-kerosene (Landälv & Waldheim, 2017).

HEFA+ production closely resembles the AJF pathway for Hydroprocessed Esters and Fatty Acids (HEFA). Traditional HEFA fuel was already certified by ASTM International in 2011, meeting ASTM's Method D7566, the "Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons," at blend levels of 50% or below (Wang et al., 2016). A re-identification provision within ASTM D7566 states that AJF blends meeting all the requirements of D7566 also meet the requirement of ASTM D1655 "Standard Specification for Aviation Turbine Fuels" and can be regarded as conventional fuels (ASTM International, 2016; IATA, 2012). Therefore, at the blend levels specified in a given fuel's D7566 Annex, that fuel is considered a "drop-in" AJF.

Producing traditional HEFA fuels requires additional hydroisomerization beyond that needed to produce renewable diesel, as kerosene has a shorter chain length than diesel. As the chains shorten, the process also creates low-value light compounds



**Figure 1.** Flow diagram of renewable diesel production process.

Source: Derived from Honeywell UOP (n.d.)

(i.e., those with shorter carbon chains) produced by the biorefinery, such as naphtha and propane (Landälv & Waldheim, 2017; Starck et al., 2016). These light compounds cannot be included in finished jet or road fuel, so reducing their share of the product stream raises the overall value of fuel production by increasing the yield of transport fuel relative to lower-value materials. To produce HEFA+, manufacturers can instead alter the HEFA process to reduce the intensity of the hydroisomerization stage of hydroprocessing, leaving longer hydrocarbon chains more similar to diesel than to kerosene.

Decreasing the yields of light compounds reduces the cold flow properties of the finished fuel relative to traditional HEFA. The reduced cold-weather performance for HEFA+ is likely not a factor in most on-road uses but takes on greater importance in aviation, where jet fuel specifications for Jet A and Jet A-1 require a maximum freezing point of  $-40^{\circ}\text{C}$  and  $-47^{\circ}\text{C}$ , respectively (Starck et al., 2016). The unblended or "neat" HEFA+ has a higher freezing point than traditional HEFA fuels, thus requiring a greater share of petroleum-derived fuel in order to meet the specifications

of D7566 relative to traditional HEFA (Starck et al., 2016). Therefore, HEFA+ testing has occurred at blend rates of 15%—substantially less than the 50% blends allowed for traditional HEFA fuel in road transport (Erämetsä, 2017; Radich, 2015).

## Deployment

### CERTIFICATION TIMELINE

At the time of writing, HEFA+ is undergoing a rigorous research process to acquire the ASTM certification D4054 "Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives." The multistage process involves aircraft and engine manufacturers and requires up to 890,000 liters of blended jet fuel to complete (Rumizen, 2013). The certification process can be lengthy, as it requires consensus from all original equipment manufacturers (OEMs) that produce airframes or engines before moving to the next stage of approval (M. Lakeman, personal communication, January 24, 2018). As part of data collection, Boeing, in collaboration with the U.S. Federal Aviation Administration (FAA) and engine manufacturers, has conducted flight tests onboard its ecoDemonstrator

787 flight test airplane, using a blend of 15% green diesel and 85% petroleum jet fuel in one engine (Boeing, 2014). The final blending allowance for HEFA+ in the ASTM standard is to be determined through further testing.

If approved, HEFA+ would be included as an annex of ASTM D7566. Once the certification process is complete, the blended fuel would be ready for use on commercial flights and could easily be integrated into common fuel delivery systems at airports. Integrating alternative fuels into operations is a relatively simple process, as illustrated by United Airlines' use of HEFA fuels. AltAir Fuels has successfully delivered blended fuel to the Los Angeles International Airport fuel farm, where it is mixed with conventional jet fuel from other providers instead of directly to United's aircraft via a dedicated delivery system (Kharina & Pavlenko, 2017).

Currently, it is uncertain when HEFA+ will be available for airlines. Past reports indicate a typical timeline of 3 to 5 years for certification (Colket et al., 2016, and Csonka, 2016). Although the process to certify HEFA+ has been ongoing for several years, it is difficult to predict when it will be completed (M. Lakeman, personal communication, January 24, 2018).

## AVAILABILITY ASSESSMENT

HEFA+ is currently available only in small volumes for testing, whereas renewable diesel for the road sector is already being produced at a commercial scale. Global renewable diesel production capacity is approximately 6 billion liters (4.7 million tonnes) as of 2017, with the majority (4.5 billion liters) located in the EU (Flach, Lieberz, & Rossetti, 2017; Greenea, 2017). Renewable diesel capacity in North America is substantially smaller, with only 1 billion liters of production capacity in 2016 and another

500 million liters of capacity under construction (Wang et al., 2016). Canada imports its renewable diesel, with zero domestic capacity in 2016 (Dessureault, 2016). Existing renewable diesel production in North America would displace only 2% of U.S. and Canadian jet fuel demand (approximately 72 million liters in 2017) (BTS, 2018; U.S. EIA, 2018).

In the EU, the majority of renewable diesel production comes from waste feedstocks such as used cooking oil and animal fats, as the industry transitions away from palm oil because of environmental concerns (Flach et al., 2017). Neste, a leading proponent of HEFA+ and Europe's largest producer of renewable diesel, generated about 80% of its renewable diesel from waste fats and oils and the remainder from crude palm oil (Flach et al., 2017). The waste feedstocks used by Neste include palm fatty acid distillates (PFADs), an oily by-product of the palm oil manufacturing process. In North America, Diamond Green Diesel and AltAir, the two largest renewable diesel producers, primarily make use of waste feedstocks such as animal fats and used cooking oil (Lane, 2017). Diamond Green Diesel has also made use of inedible corn oil, a by-product of corn ethanol production, to manufacture its renewable diesel (CARB, 2017a). Although much existing production of renewable diesel comes from wastes and by-products, this does not guarantee that future production in response to increased demand would come from those sources.

There is limited potential for expanding the production of HEFA+ by diverting waste oils and fats from other uses. The supply of waste feedstocks such as used cooking oil, animal fats, tall oil, and PFADs is fixed and will not increase with demand for these wastes. For example, tallow represents a small fraction of an entire cow

carcass and has lower value than meat; a farmer will thus decide whether to increase or decrease livestock production based on the price of beef rather than the price of tallow, which has a smaller impact on profits. We may expect the supply of tallow to increase if total beef production increases, but it will not change as a result of biofuel policies. Figure 2 shows current total production of major types of waste and residual HEFA+ feedstocks in the United States and Canada. This figure shows the breakdown of feedstock use in biodiesel versus other uses, including livestock feed and industrial products (data on feedstock use in renewable diesel or other types of biofuel are not available). Also shown is the maximum share of U.S. jet fuel consumption that could be supplied by HEFA+ if the entire supply of these feedstocks were used for this purpose. Waste and residual fats and oils could supply as much as 7% of total jet fuel demand in the United States and Canada.

However, we emphasize that diverting 100% of waste and residual fats and oils to biofuel production would be neither practical nor environmentally beneficial. Drastically increasing the demand for these materials would sharply increase their prices, which would lead to substantially higher overall costs for HEFA+. The environmental impacts of increasing the use of waste oils and fats in HEFA+ are described below.

## ENVIRONMENTAL PERFORMANCE

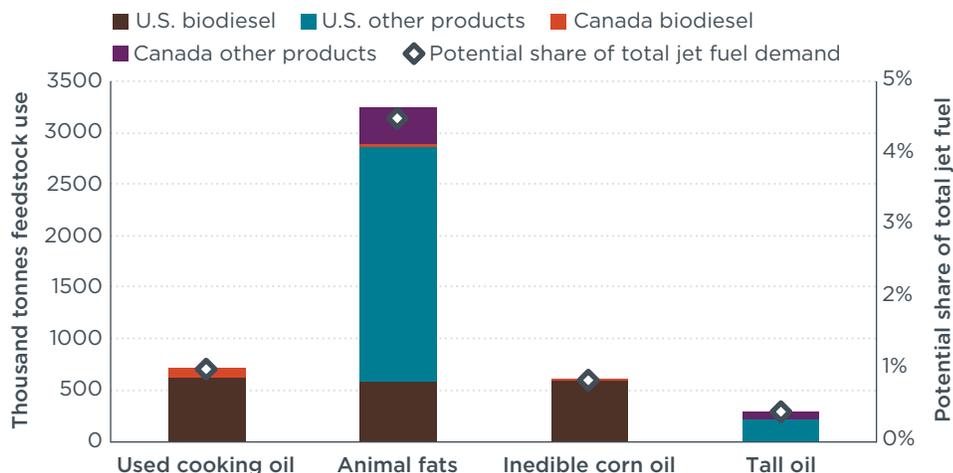
Producing synthetic diesel from vegetable oils and waste fats avoids some of the impurities found in crude oil that generate air pollution upon combustion, such as sulfur. Relative to petroleum diesel, renewable diesel used in the road sector has been found to produce equivalent or lower criteria air pollutant emissions. For example,

the California Air Resources Board finds that relative to petroleum diesel exhaust, renewable diesel exhaust contains less particulate matter (PM), NO<sub>x</sub>, and carbon monoxide (California EPA, 2013). Preliminary testing by Boeing indicates that the reduction in soot formation with fuels like HEFA and HEFA+ may deliver benefits for aircraft, reducing the maintenance requirements for the engines (M. Lakeman, personal communication, January 24, 2018).

The carbon intensity of HEFA+ can vary widely depending on the choice of feedstock used for production. HEFA+ can be produced from a wide variety of fatty feedstocks, including virgin vegetable oils made from oilseeds such as soy and palm, as well as waste oils and fats such as used cooking oil and inedible animal tallow. The carbon intensity of the finished fuel includes both direct and indirect emissions.

Direct emissions for HEFA+ production are primarily attributable to the fuel production and processing phase and are comparable across different feedstocks. Because of the similarity in production methods between renewable diesel for the road sector and HEFA+ for aviation, we can reference lifecycle assessments of renewable diesel to understand the climate impacts of HEFA+. For example, the GHGenius Model estimates a lifecycle emission factor of 18.0 gCO<sub>2</sub>e/MJ and 12.7 gCO<sub>2</sub>e/MJ for renewable diesel produced from canola oil and yellow grease, respectively ((S&T)<sup>2</sup> Consultants, 2012).<sup>1</sup> These values are roughly comparable to the direct emissions for certified renewable diesel pathways within California's Low-Carbon Fuel Standard (LCFS),

<sup>1</sup> Assuming a renewable diesel density of 770 g/liter and a lower heating value (LHV) of 44.1 MJ/kg.



**Figure 2.** Total feedstock production and use of potential HEFA+ feedstocks, and maximum potential production of HEFA+ from these feedstocks, as a share of total jet fuel demand in the United States and Canada.

*Sources and assumptions:* Quantities used in U.S. biodiesel production in 2015 from U.S. EIA (2017); quantities in U.S. non-biodiesel uses for used cooking oil, animal fats, and inedible corn oil from Nelson and Searle (2016); U.S. tall oil production from Peters and Stojcheva (2017); quantities used in Canadian biodiesel production in 2016 from Dessureault (2016); total animal fats production in Canada from FAO (2018); Canadian tall oil production estimated to be proportional to production in the United States by total revenue of each country's pulp and paper industries; Canadian non-biofuel uses of inedible corn oil assumed to be zero following Nelson and Searle (2017); Canadian non-biofuel uses of used cooking oil assumed to be zero because the quantity used in Canadian biodiesel production exceeds the supply of collected U.S. used cooking oil on a per capita basis.

which are approximately 20 gCO<sub>2</sub>e/MJ for soybean oil-derived renewable diesel and 15 to 20 gCO<sub>2</sub>e/MJ for used cooking oil-derived renewable diesel. In comparison, the baseline well-to-wake (WtWa) emissions for petroleum-based diesel are approximately 90 gCO<sub>2</sub>e/MJ (Elgowainy et al., 2012).

Many feedstocks can also generate indirect emissions from outside their immediate production process. The use of land-based crops, including all types of food commodities, for biofuel causes indirect land-use change (ILUC) emissions, as the increased demand for these commodities drives land conversion beyond the cropland directly used for feedstock cultivation.

The use of waste oils and fats for biofuel production can generate indirect emissions. Diverting waste oils and fats from other uses may lead to increased production of virgin vegetable oils as

substitute materials. For example, used cooking oil has historically been used in livestock feed in the United States (Nelson & Searle, 2016). Diverting it to biofuel production reduces the fat content and overall quantity of livestock feed. Livestock farmers must thus replace it with another oil or fat, such as palm oil. This increases the overall demand for palm oil and drives expansion of palm oil production. Using wastes and residues that have existing uses for HEFA+ production will thus necessarily result in increased emissions from the production of additional crops and the land-use change emissions associated with their expansion (see Figure 3).

Taking indirect emissions for HEFA+ into account can substantially change our understanding of the GHG benefits of this fuel relative to petroleum jet fuel. For some feedstocks, indirect emissions can undermine the supposed

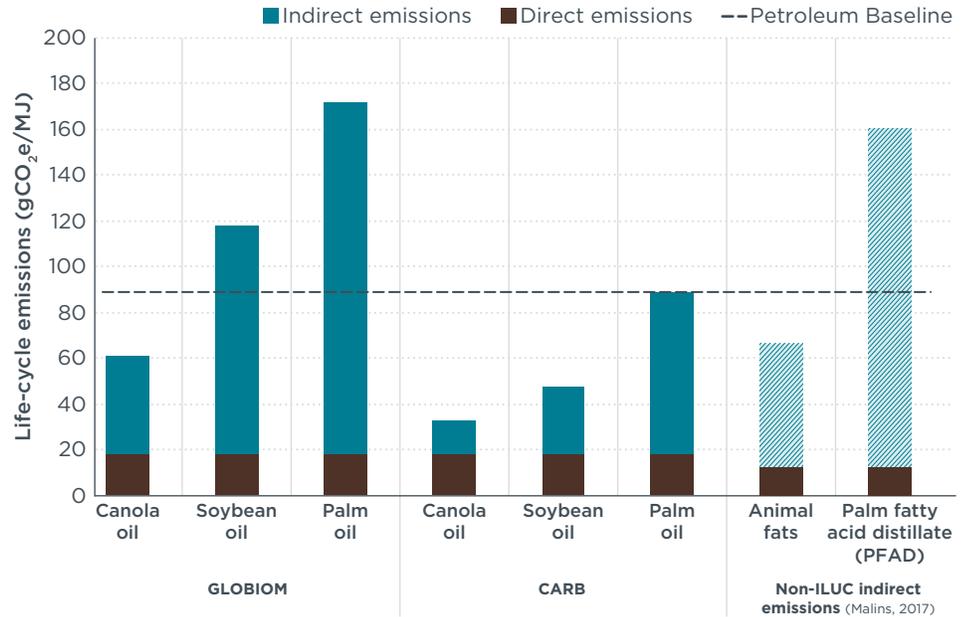
GHG reductions attributable to fuel switching. Previous ILUC estimates for oilseeds suggest a wide range of possible values. In particular, palm oil-derived fuel generates high ILUC emissions because a large share of oil palm expansion occurs on drained peatlands and high-carbon forestland in Southeast Asia. ILUC estimates conducted in support of Europe’s Renewable Energy Directive (RED) and California’s LCFS indicates that ILUC from palm oil-derived fuels can push their overall carbon intensity above that of baseline petroleum diesel fuel (see Figure 3). ILUC modeling suggests that palm oil may be a substitute for other vegetable oils when they are diverted for biofuel production. Diverting crops such as soy and canola for biodiesel causes some additional palm plantation expansion because it is often the lowest-cost alternative; this relationship drives up the ILUC emissions for all oilseed-derived biofuels.

### Policy Implications

Manufacturing renewable diesel may be cheaper than producing jet fuel from sugars or lignocellulosic feedstocks, but it is still reliant on policy incentives and subsidies for its viability.

AJFs are still more expensive to produce than conventional fossil fuels, although the price gap has narrowed in recent years for some fuels (M. Lakeman, personal communication, January 24, 2018). The policy context of where AJFs are produced is critical to determining the cost-effectiveness of fuel switching; some renewable diesel producers in the United States have begun to approach the cost of conventional fuels after factoring in the value of policy incentives (Kharina & Pavlenko, 2017; Lakeman, personal communication).

ICAO is in the process of developing a methodology for crediting fuel switching through its Carbon Offsetting and



**Figure 3.** Impact of indirect emissions on carbon intensity of renewable diesel for several different feedstocks.

Note: the partially-shaded columns reflect preliminary indirect diversion emissions estimates from Malins (2017), rather than ILUC values developed to inform fuels policies.

Source: Direct emissions values (in brown) taken from GHGenius ((S&T)2 Consultants, 2012); indirect emissions values taken from CARB (2018), Malins (2017), and Valin et al. (2015). Indirect diversion emissions estimates from Malins (2017) include upstream production emissions, land-use change, forest carbon debt, and fossil fuel emissions.

Reduction Scheme for International Aviation (CORSIA), where alternative fuels are part of a basket of measures eligible for meeting ICAO’s GHG target of carbon-neutral growth. On the basis of the draft Standards and Recommended Practices (SARPs) released for State consultation, it is likely that HEFA+ fuels would be eligible for crediting within CORSIA, although the extent of the GHG reductions generated would depend on the feedstock used (ICAO, 2017b). It is still highly uncertain how strong of a price signal CORSIA will send for alternative fuels, as out-of-sector carbon offsets are likely a much cheaper source of GHG reductions (Pavlenko et al., 2017). ICAO has also introduced a separate alternative fuel goal; however, it is broad and aspirational. In the absence of a specific volumetric target or incentive, it is up to member states

to establish policy incentives for AJFs (ICAO, 2017a).

Several countries are considering incentivizing AJFs through a variety of policies. In North America, the primary policy incentive for AJF production is the U.S. Renewable Fuel Standard (RFS). The RFS supports AJFs on an “opt-in” basis, wherein they can be produced in order to generate renewable identification number (RIN) credits, but aviation is not an obligated sector (U.S. EPA, 2010). This means that while aviation fuels can qualify for RINs, aviation fuel suppliers are not obligated to meet RFS quotas on fuel blending. RINs are tradeable credits that demonstrate compliance with the RFS; AJF producers can sell them to obligated parties such as fuel blenders and refiners to supplement their income. RINs are categorized

into several different codes based on their feedstock type and level of GHG reduction. Currently, AJFs produced from waste oils and fats qualify for D5 RINs for “advanced biofuels,” which can sell for approximately USD \$0.34 per renewable diesel-equivalent liter.<sup>2</sup> Although several different food-based feedstocks such as soy and canola are approved under RFS, HEFA+ production from palm oil specifically would not qualify for RINs unless it is produced at grandfathered facilities that were producing fuel in 2007 or earlier.

California will likely amend its LCFS to include AJF as an eligible opt-in fuel in by 2019 (CARB, 2017). This could create a substantial market for AJF in California, as the incentive value from LCFS could be combined with the RIN credits generated under the U.S. RFS. The LCFS is a performance-based standard in which fuel producers generate credits according to the carbon intensity of the finished fuel relative to the fossil baseline; the value of the credit is derived from both the carbon reduction from the fuel and the trading price of LCFS credits. LCFS credit values can vary greatly, with ranges from \$20/tonne CO<sub>2</sub>e in 2015 to more than \$140/tonne CO<sub>2</sub>e in early 2018 (CARB, 2018b). At the time of publication, a liter of used cooking oil-based renewable diesel would be eligible for an incentive of USD \$0.34 per liter (CARB, 2017a, 2018a).<sup>3</sup> As with the U.S. RFS, HEFA+ production from palm oil would likely fall above the fossil fuel baseline and thus be ineligible for credit generation in California’s LCFS.

2 Assuming an energy-equivalence value of 1.7 for non-ester renewable diesel.

3 Estimated using the LCFS Credit Price Calculator with an assumption of a credit price of \$140/tonne CO<sub>2</sub>e and a carbon intensity of 20.28 gCO<sub>2</sub>e/MJ.

Environment and Climate Change Canada’s framework document on the proposed Clean Fuel Standard (CFS) suggests that Canada may also introduce a federal incentive for AJFs (ECCC, 2017). At the time of publication, the proposed CFS will be a performance-based standard that incentivizes fuels on the basis of their carbon intensity across three broad pools of fuel: liquid, gaseous, and solid. This approach would not include any sector-specific goals and could allow AJF production to qualify for the purposes of meeting the CFS target of 30 million tonnes of CO<sub>2</sub>e reductions by 2030. Furthermore, the proposed policy will exclude indirect emissions accounting, thereby allowing a wide variety of possible feedstocks to qualify within the program.

In the aviation industry, AJF proponents commonly advocate for a level playing field for AJF and alternative road fuels (IATA, 2015). As North American fuels policies begin to shift toward allowing aviation fuels to opt in and receive the same treatment as fuels used in the road sector, it is still unclear whether the aviation sector can out-compete the road sector for a limited supply of low-carbon biofuels made from sustainable wastes and by-products. Because the road sector is already obligated to transition to alternative fuels and is subject to fuel taxes, it is able to support higher fuel prices. The final price of diesel and gasoline in the road sector reflects fuel taxes and the costs associated with compliance for road-sector policies such as sulfur limits and the RFS. In contrast, the international aviation sector is accustomed to lower fuel prices because aviation fuel is untaxed; consequently, it has a lower willingness-to-pay and would likely support lower prices for finished fuels than the road sector (El Takriti, Pavlenko, & Searle, 2017).

If more favorable policies were put in place, it is possible that AJF production could divert a limited supply of sustainably available feedstocks from existing renewable diesel supply for the road sector. However, the climate benefit of this shift would be questionable. For example, in a best-case scenario where strong incentives shift the existing production of renewable diesel from wastes and by-products toward the aviation sector, there is likely not sufficient feedstock supply to compensate for that diversion within the road sector. In effect, this would simply shift existing emissions reductions (or emissions increases in some cases, such as palm oil) from the road sector toward aviation, and at a higher policy cost. Furthermore, in the absence of strong policy safeguards on sustainability and ILUC, an increase in net demand for HEFA+ and renewable diesel may result in additional production of food crops such as oil palm and soybean, undermining the benefits of alternative fuels policies.

## Conclusion

The introduction of HEFA+ fuel presents an opportunity to ramp up the consumption of AJFs substantially in the short term, as this fuel is already produced at a commercial scale worldwide for the road sector as renewable diesel. HEFA+ alone cannot meet the necessary performance specifications for jet fuel, but there is evidence that at low blend levels (15% or below) it can be incorporated into existing aircraft with minimal drawbacks. Although HEFA+ production could displace large volumes of petroleum jet fuel, generating large volumes of alternative fuel alone is not a meaningful policy goal. Rather, policymakers should focus on making meaningful GHG reductions; simply supporting greater volumes of HEFA+ fuels will not ensure this outcome.

The carbon intensity of HEFA+, as with renewable diesel in the road sector, is strongly dependent on the feedstock used to manufacture the fuel. HEFA+ feedstocks include vegetable oils, used cooking oil, and animal tallow. Increased demand for virgin vegetable oils can cause upward pressure on land use and competition with the food sector, generating ILUC emissions. The waste and by-product feedstocks used for HEFA+, such as used cooking oil, are already nearly fully utilized within the road sector, and evidence of the benefits of using these feedstocks for AJFs is undermined

by the indirect emissions caused by their diversion from their existing uses. Lignocellulosic feedstocks with much higher availability and lower indirect effects are unlikely candidates for the HEFA+ process, limiting the ability of HEFA+ to meet the aviation sector's ambitious climate goals.<sup>4</sup>

The existing framework of fuels policies in North America could feasibly support HEFA+ production in the near future, but it is unclear whether an even playing field with the road sector will be a strong enough driver to divert existing renewable

diesel production away from the road sector. Without a strong price signal from the CORSIA program, airlines may not be able to afford the price premium for renewable diesel production relative to the current price of petroleum-based diesel. Furthermore, if HEFA+ demand were to lead to increased overall production of renewable diesel, it is likely that the additional production would come from vegetable oil feedstocks with dubious climate benefits. Therefore, HEFA+ fuels are unlikely to be a key pathway to decarbonization of the aviation sector.

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4 The relative GHG benefits and sustainable availability of lignocellulosic feedstocks for AJF production in North America are explored in more detail in Pavlenko (2017).

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