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BRIEFING

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Alternative Jet Fuel Development and Deployment in North America

International aviation emissions of greenhouse gases (GHGs) from airline carriers based in Canada and the United States increased from 36.2 to 60.2 million tonnes ($MtCO_2e$) per year from 1990 through 2015—and they are projected to keep growing by 2.6% each year through 2035. Globally, international aviation emissions are projected to grow at a faster rate—4.3%—through 2035 (ATAG, 2016).[1] The International Civil Aviation Organization (ICAO)—the United Nations agency that coordinates international standards for civil aviation—has committed to minimizing the industry's environmental impacts. ICAO's three major environmental goals consist of limiting aircraft noise, improving local air quality, and reducing GHG emissions.

From 1980 through 2015, the fuel efficiency of new aircraft (measured in units of fuel consumption per revenue-tonne-kilometer) increased by approximately 1% annually, on average (Kharina & Rutherford, 2015). In 2016, ICAO's Committee on Aviation Environmental Protection introduced a carbon dioxide (CO_2) standard that mandates a 4% reduction in the cruise fuel consumption of new aircraft starting in 2028 compared to 2015 deliveries (ICAO, 2016; ICCT, 2016). In addition, several airlines and airports have begun deploying alternative jet fuels (AJFs) in a piecemeal fashion—either in limited blends on test flights or on select routes. Together, these efforts are unlikely to make a substantial contribution toward meeting ICAO's target of carbon-neutral growth by 2035.

1 The projected rate of emissions growth includes a 1.5% annual reduction in fuel burn through improved technology and operations. Reference updated on June 16, 2017.

Prepared by Nikita Pavlenko. This work was completed under the generous support of Environment and Climate Change Canada.

Although the bulk of aviation emissions come from fuel burn, improving the fuel efficiency of aviation through new aircraft types and operational improvements can only partially offset the increase in emissions resulting from a higher volume of air travel. Kharina, Rutherford, and Zeinali (2016) estimate that the fuel burn of new aircraft designs beginning in 2024 and 2034 can be reduced by approximately 25% and 40%, respectively, in a cost-effective manner relative to current designs. However, even if this level of efficiency improvements fully penetrates the market, it would not be enough to prevent future increases in aviation emissions.

To facilitate the remaining reductions, ICAO introduced the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) at its 39th Assembly meeting—the first time a market-based measure (MBM) has covered an entire sector internationally. CORSIA offers a phased implementation; the first two phases (the pilot phase, 2021–2023, and Phase 1, 2024–2026) are voluntary, and Phase 3 (2027–2035) is mandatory to most aviation traffic.[2] Under CORSIA, airlines can reduce a portion[3] of their GHG emission growth through implementing efficiency improvements, switching to fuels with lower carbon intensities, or reducing emissions outside the sector through the purchase of carbon offsets.

Both Canada and the United States have committed to the voluntary phases of CORSIA. Assuming total projected emissions of 69 Mt in 2020 and an annual growth rate of 2.6% that factors in ongoing technology efficiency improvements, international aviation operations from these two countries would approach 103 Mt annually in 2035. Therefore, cumulatively, Canadian and U.S. international carriers would need to offset 250 Mt of CO_2, as shown in Figure 1. Increasing the consumption of lower carbon alternative fuels has been identified by ICAO as a potential method to reduce international aviation emissions, in addition to efficiency improvements and purchasing offsets. As part of this strategy, North America could be well-positioned to develop its own low-carbon AJF from the domestic feedstock supply.

2 "Second phase (from 2027 through 2035) would apply to all States that have an individual share of international aviation activities in RTKs in year 2018 above 0.5 per cent of total RTKs or whose cumulative share in the list of States from the highest to the lowest amount of RTKs reaches 90 per cent of total RTKs, except Least Developed Countries (LDCs), Small Island Developing States (SIDS) and Landlocked Developing Countries (LLDCs) unless they volunteer to participate in this phase." (http://www.icao.int/environmental-protection/Pages/A39_CORSIA_FAQ2.aspx)

3 From 2021 through 2029 (from the pilot phase through the first 3 years of Phase 2, CORSIA's emissions-reduction obligations are based on the average emissions growth rate of the industry. From 2030 onward, the offsetting requirements transition to reducing portions of the individual airline carriers' own growth since 2020.

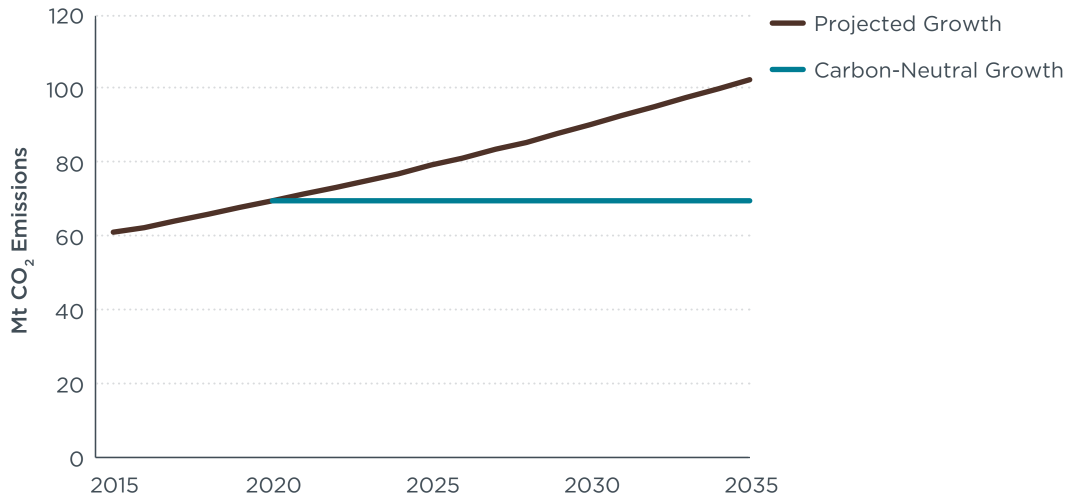

Figure 1. Projected growth in Canadian and U.S. international aviation emissions, 2015–2035

Note: Derived from Environment and Climate Change Canada (2016), ICAO (2013), and U.S. EPA (2016). "Projected growth" scenario includes 1.5% annual improvement in efficiency.

The wide variety of possible AJFs makes designing a comprehensive aviation fuels strategy for carriers a complex endeavor. Therefore, it is critical to assess the extent to which different types of fuels offer meaningful GHG reductions, and at what cost. In this policy brief, we review the environmental performance, potential cost, and availability of potential AJFs that could be used in North America. We then explore the role that AJF could play in reducing international aviation emissions in North America and provide recommendations for policymakers on aligning aviation fuel policy with the GHG reductions of CORSIA's three phases.

SUSTAINABILITY OF AJFS

AJFs come from a variety of different sources and can have significant variation in composition and environmental performance.

AJFs can be broken down into several broad categories depending on the feedstock (i.e., the material converted into fuel) and processing method. Generally, oils and fats, whether from virgin vegetable oils or recovered from waste, require the simplest technologies to be converted into AJF. These technologies are the closest to commercialization and have been the most deployed in test flights.

Converting sugars and cellulosic feedstocks into fuels is slightly more complex than converting oils into fuel and is further away from commercialization. Examples of feedstocks that could be converted into fuel include food crops, such as corn, and energy crops, such as switchgrass, miscanthus, and short-rotation coppice. Food crops like corn and sugarcane have readily accessible sugar that can be fermented to produce ethanol, which is then converted into a hydrocarbon thermochemically. Cellulosic feedstocks, which typically consist of woody or grassy biomass, require an additional step to break down their tough lignocellulosic material into sugars for fermentation; thus, fuels from cellulosic feedstocks are further away from commercialization than fuels made from food crops.

There are also several potential AJFs that do not require biological feedstocks. For example, the power-to-liquids (PtL) process uses renewable electricity to generate hydrogen, which is then combined with captured CO_2 to produce a "drop-in" fuel (Schmidt, Weindorf, Roth, Batteiger, & Riegel, 2016). Large-scale PtL deployment is restricted by a variety of factors, particularly the cost and availability of substantial amounts of renewable electricity.

Currently, the cheaper and more abundant feedstocks generally require more advanced technology and are more expensive to convert into fuel, whereas more expensive feedstocks, such as vegetable oils, require relatively little processing. For each feedstock category, a variety of conversion processes may be used to produce an AJF. The specifications of the finished fuels may differ based on the processing pathway—some fuels are more like petroleum jet fuel and may be blended in higher concentrations than others.

To make meaningful GHG reductions through fuel switching, care must be taken to identify and support the fuels with the lowest environmental impacts. Policymakers can compare the environmental performance of different fuels by using life-cycle analysis to assess GHG emissions. Fuels that offer low life-cycle carbon intensity in conjunction with high feedstock availability have the greatest potential for displacing petroleum and substantially reducing sectoral GHG emissions.

The production of AJF can cause GHG emissions both directly and indirectly. The direct components of the alternative fuel life-cycle include the energy and emissions associated with feedstock cultivation, land use, processing, transport, and final combustion. The indirect emissions from alternative fuels include the emissions resulting from market-mediated responses to increased biofuel demand. For example, indirect land-use change (ILUC) occurs when increased demand for food-based feedstocks, such as corn or canola oil, increases the prices of those commodities. This, in turn, decreases food security and increases demand for additional land to grow those feedstocks, generating GHG emissions from new land conversion. ILUC emissions are typically estimated using economic models of agricultural supply and demand that project shifts in land use in response to a demand shock from a biofuel policy.

El Takriti, Pavlenko, and Searle (2017) conduct a literature review of various life-cycle analyses of AJFs, combining the direct emissions from feedstock collection and processing with the indirect emissions associated with ILUC. The study finds that overall food-based AJFs, particularly vegetable oil–based fuels derived from feedstocks such as palm, soybean, and canola, had the highest carbon intensity of all of the AJFs assessed. One reason for this is the fungibility of vegetable oils; as more of these feedstocks are used for AJF production, the resulting increase in vegetable oil prices drives increased imports of palm oil for use in non-energy sectors (Santeramo, 2017). This substitution effect is reflected in some modeling studies. Emissions from vegetable oil–based fuels in some cases exceeded the baseline carbon intensity of petroleum jet fuel when indirect effects were included, suggesting that transitioning to these fuels could undermine the aviation sector's GHG targets. Starch and sugar crops occupy the middle tier of results, because their indirect effects are substantially lower than for vegetable oils, according to a meta-analysis of AJF life-cycle analysis (El Takriti et al., 2017). This category had the most substantial variation in results, suggesting minimal to moderate reductions in GHG intensity.

AJF pathways using energy crops, wastes, and residues assessed in El Takriti et al. (2017) offered the best results. Wastes and byproducts, such as tallow and used cooking oil, were found to offer substantial reductions of carbon intensity relative to baseline petroleum jet, on the order of 50% to 80%. Likewise, fuels made from agricultural residues, such as corn stover and forestry residues, were found to offer GHG reductions of 70% to 90% relative to petroleum jet fuel. Energy crops, which most studies estimate to have low ILUC impacts, performed similarly to agricultural residues. PtL and waste gas conversion, both of which use captured CO_2 and carbon monoxide (CO) to produce liquid fuels, offered some of the highest reductions, approaching 90% reduction in carbon intensity if renewable electricity is used.

Figure 2 shows an illustration of the net GHG emissions of various AJF pathways, accounting for both direct and ILUC emissions taken from several different modeling studies. When ILUC is factored in, emissions from common, food-based feedstocks tend to be higher. Energy crops, wastes, and residues are generally associated with lower ILUC emissions compared to food crops (Searle, Petrenko, Baz, & Malins, 2016). According to GLOBIOM modeling, palm- and soy-based AJFs would exceed the baseline carbon intensity of petroleum jet fuel on the basis of ILUC alone, even before accounting for their direct emissions.

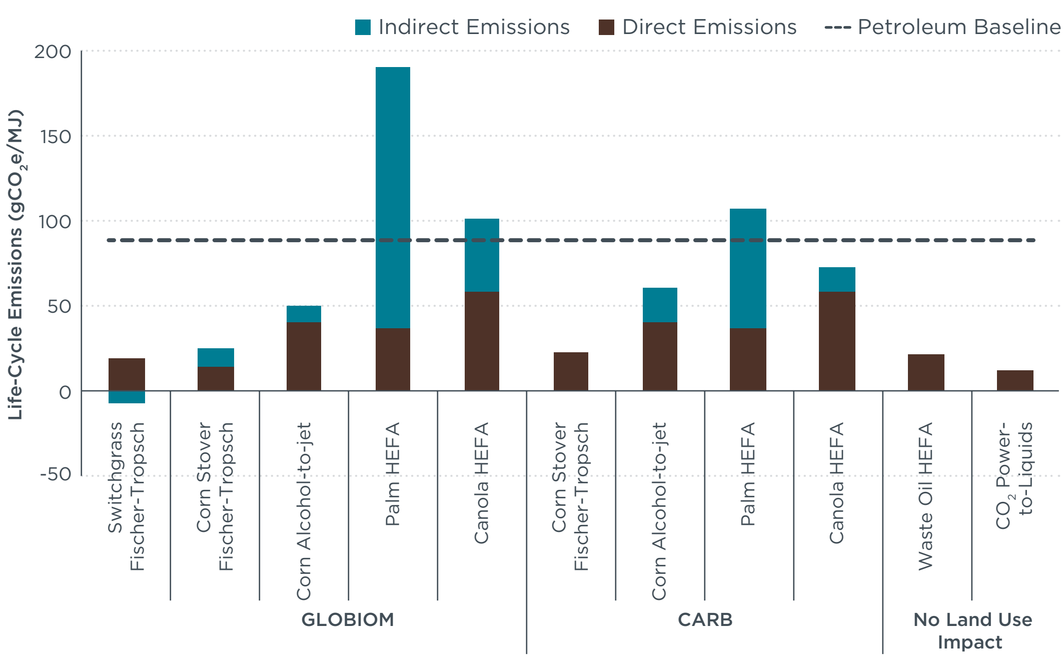

Figure 2: Life-cycle emissions from jet fuel production for selected AJF feedstocks and pathways*

Note: Adapted from CARB (2017b), Elgowainy et al. (2012), GREET (2017), Schmidt et al. (2016), Seber et al. (2014), and Valin et al. (2015)

**Figure revised on June 16, 2017.*

Beyond GHG impacts, consideration must be given to other sustainability considerations associated with AJFs. Some key considerations include preserving soil health, air and water quality, biodiversity, and food security. In particular, agricultural and forest residues should be harvested sustainably to prevent soil carbon and nutrient depletion.

Overall, a comparison of life-cycle analysis results for different AJF options suggests that the steepest reductions come from utilizing either wastes or cellulosic feedstocks to produce AJF. Given the blend constraints of existing certified AJFs by ASTM International and the steep emissions reductions mandated under CORSIA, these results suggest that carriers should transition to the waste-based and cellulosic feedstocks that offer the highest reductions, leapfrogging the food-based feedstocks.

OPPORTUNITIES TO DEPLOY AJF IN NORTH AMERICA

Deploying sustainable, low-carbon AJFs in North America is feasible because of the region's high availability of sustainable feedstocks, nascent alternative fuels industry, and existing policy incentives for alternative fuels. The U.S. Renewable Fuels Standard (RFS) already includes AJFs and other advanced fuels within its approved pathways, and the California Low-Carbon Fuels Standard (LCFS) is developing criteria to assess the carbon intensity of jet fuels and include AJF pathways within the program (CARB, 2017a). Likewise, Canada is developing a Clean Fuels Standard policy based on British Columbia's LCFS approach; this new policy may include the aviation sector, offering compliance credits relative to carbon-intensity reductions (Environment and Climate Change Canada, 2017).

Several ventures in the United States are already producing AJF and have plans to scale up quickly. AltAir, based in California, has agreed to supply up to 15 million gallons of AJF to United Airlines over a 3-year period via LAX airport (Lane, 2015). This would be a fraction of 1% of United Airline's 1.5 billion gallons of fuel consumption in 2015. AltAir's fuel is an ASTM-certified drop-in product derived from waste fats and oils, offering up to an 85% decrease in carbon intensity relative to petroleum jet fuel. Another project in California, Fulcrum Bioenergy, has developed a process to convert municipal solid waste into liquid fuel, securing funding to develop several facilities that will begin to come online starting in 2018 (Sapp, 2016). Fulcrum Bioenergy has already signed 10-year agreements with Cathway Pacific and British Petroleum (British Petroleum, 2016; Lane, 2014). By 2025, Fulcrum Bioenergy aims to generate over 85 million gallons of jet fuel per year, producing a fuel that is 80% less carbon-intensive than petroleum jet fuel. Red Rocks, based in Oregon, has a 12 million gallon-per-year facility utilizing forestry residues converted via a Fischer-Trospch process and has offtake agreements with FedEx and Southwest Airlines (Radich, 2015).

There could be a substantial amount of low-carbon AJF feedstock in North America. The U.S. Department of Energy's *Billion-Ton Report* assesses the potential bioenergy supply in the United States toward 2040 across a variety of different economic scenarios and at different feedstock price levels. The middle-price scenario projects that by 2030 there would be approximately 350 million tonnes of agricultural resources available, comprised of approximately 50% energy crops, 40% agricultural residues, and 10% woody crops (i.e., short-rotation plantations of poplar and willow; U.S. DoE, 2016). Notably, the study finds that the availability of agricultural residues and cellulosic energy crops is highly sensitive to price; demand that drives up the price of those feedstocks would substantially increase the availability of crop residues in the short-term while supporting the development of increased energy cropping within the next decade. It is important to emphasize that there are many competing demands for biomass, such as heat and power generation and building materials; transportation fuels use less than 10% of the current global bioenergy demand (IEA, 2017). The road sector may also consume far greater quantities of potentially available low-carbon biofuel feedstocks than does aviation; jet fuel only comprises approximately 11% of U.S. transportation fuel consumption (EIA, 2017).

Used cooking oil and other types of waste fats are already being used to produce AJF by ventures such as AltAir, although the future supply of these feedstocks is likely to be constrained (i.e., used cooking oil is produced in proportion to food processing). U.S. DoE (2016) found that the growth in trap grease and food-processing wastes is expected to marginally increase from 2017 through 2040 and that only an additional 4.7 million dry tonnes could be available in 2030. This is corroborated by Nelson & Searle (2016), who estimate that existing uses for vegetable oils and waste fats in the road transport, livestock, and industrial sectors uses up nearly the entirety of the existing supply, and, considering current trends, growth in production of these feedstocks is expected to be minimal.

The supply of low-carbon feedstocks for AJFs depends strongly on the price they can command on the market. At the same time, the aviation industry is highly sensitive to fuel price. This stems from several factors: fuel prices are one of the largest variable costs for airlines, diesel fuels command higher prices than jet fuels because of stricter limits on sulfur content in the road sector, and international aviation fuel costs are not subject to the same taxes as road fuels (ICAO, 2006; Radich, 2015). Production costs for AJF from lignocellulosic pathways are estimated to be $1,000–$8,000/tonne, whereas conventional jet fuel costs ~$470–$860/tonne (El Takriti et al., 2017). This dynamic may create difficulties for AJF producers, who must compete with potential buyers for feedstocks in other sectors, which may be able to offer higher prices for finished fuels.

The annual jet fuel demand for international aviation in Canada and the United States is projected to increase to 1,430 GJ by 2035 (approximately 10 billion gallons of fuel). In contrast, only 112 million gallons of low-carbon AJF are projected to be readily available by 2025, based on the existing supply agreements described above—less than 1% of jet fuel demand. That level of supply would barely shift the overall international aviation emissions in North America. Because biomass use in heat, power, and road transport has an economic advantage over use in AJF, the AJF industry is unlikely to bid away more than a small fraction of the total feedstock supply. If, for example, we assume that the aviation sector would have access to 3% of the available agricultural biomass from residues and energy crops in 2035 (approximately 10.5 million tonnes), that would translate to an additional 640 million gallons of ultralow-carbon AJF.[4] This would be equivalent to displacing approximately 8% of North American jet fuel consumption with ultralow-carbon biofuels by 2035. PtL fuel production could also theoretically provide a portion of 2035 supply, although the exact share would be highly speculative because the technology is far from commercialization and relies on the availability of renewable electricity.

4 Assuming a jet fuel energy density of 142 MJ/gallon; a conversion efficiency for Fischer-Tropsch of 0.6 MJ/MJ; and a weighted average energy density of 18 MJ/kg for agricultural residues, energy crops, and forestry residues.

If the U.S. and Canadian aviation sectors secure 3% of the DoE's projected available agricultural biomass from residues and energy crops, that would supply nearly 800 million gallons of fuel by 2035. If we assume that this fuel consists of Fischer-Tropsch renewable jet fuel with a carbon-intensity reduction of 80% (i.e., 18 gCO_2e/MJ), international aviation emissions could be abated by approximately 6.4 Mt annually by 2035—approximately 20% of the amount needed to meet the carbon-neutral growth target. The emissions projection presented in Figure 3 shows that AJFs alone are unlikely to allow carbon-neutral growth for North American international aviation. Although, in theory, AJFs could deliver the remaining reductions, extremely strong policy support would be necessary, and sustainable feedstocks could be diverted away from other sectors. If policies incentivize the use of AJFs with a higher carbon intensity, such as hydro-processed esters and fatty acid (HEFA) biofuels made from vegetable oil, the CORSIA target would be even further out of reach based on AJF alone.

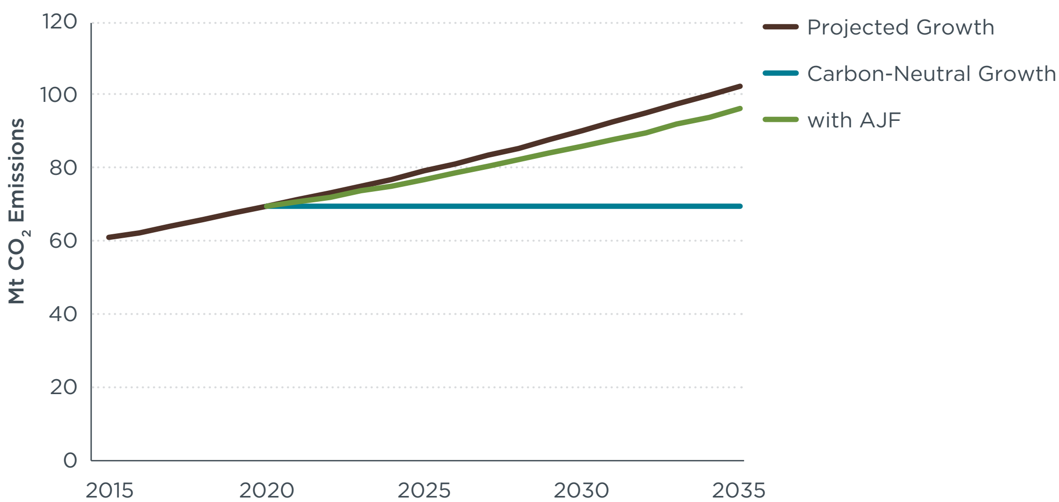

Figure 3: Projected impact of ultralow-carbon AJF deployment on international aviation emissions in Canada and the United States

The relatively high costs of AJF production could also prove to be a barrier to AJF deployment and further decarbonization. Fuel production is much more expensive than the cost of purchasing carbon offsets, which range from $1 to $130/tonne of CO_2 abated, with 85% of emissions being priced at less than $10/t$CO_2$ (Kossoy et al., 2015). Even lower cost offsets, such as United Nations Framework's certified emission reductions, which as of March 2017 were trading at 0.40 euros per tonne, are also under consideration (Carbon Pulse, 2017). In comparison, the actual purchase prices of agricultural residue-derived and sugar-derived AJFs for the U.S. Department of Defense ranged from $3,091 to $8,983/tonne, respectively (International Air Transport Association [IATA], 2014). Theoretical models of future AJF production estimate that production costs of novel technologies will decrease. IATA (2014) estimates that the theoretical cost of producing AJF using the Fischer-Tropsch (F-T) method from switchgrass is lower, with a range of $1,876 to 3,329/tonne. The costs of producing AJF from food crops is projected to be cheaper because of the simpler technology. Pearlson, Wollersheim, and Hileman (2013) estimate that the cost of producing HEFA jet fuel from soybeans would range from $1,334 to $1,532/tonne.

Figure 4 shows that after normalizing on the basis of GHGs reduced per dollar spent, however, the switchgrass-based fuel with a lower carbon intensity proves to be substantially more cost-effective than soybean HEFA fuel at reducing emissions, although it is still much more expensive than offsets. Depending on the cost of the fuel and its life-cycle GHG emissions (see the range in Figure 2), the cost of emissions reductions could vary from $270/tonne to well over $2,000 per tonne.

In the case of soybean HEFA, if ILUC brings the carbon intensity of a fuel close to that of petroleum jet fuel, the cost of emissions reductions increases sharply, toward the upper end of the chart.

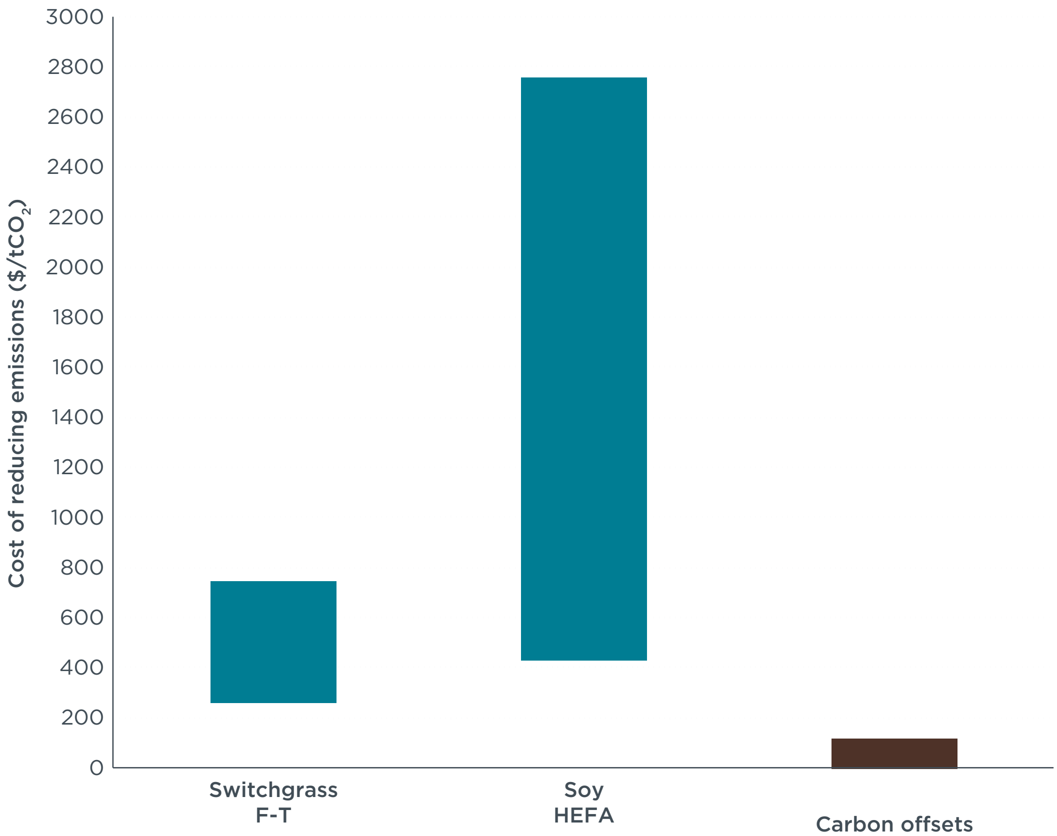

Figure 4: Range of potential costs for reducing emissions by AJF and carbon offsets

Even at the low end of this price range, fuel-switching costs are substantially higher than the projected direct offsetting cost of CORSIA, which is estimated to stay below 1% of fuel prices until 2030 (ICCT, 2017). The effectiveness of CORSIA at incentivizing GHG reductions from individual airlines will be further diluted by using an industry average emissions growth during the initial phases of the program (through 2029). Even after 2030, once CORSIA's obligations transition to offsetting individual airlines' emissions growth, the cost of transitioning to a novel, ultralow-carbon AJF would likely dwarf CORSIA's costs. This suggests that CORSIA on its own is unlikely to promote fuel switching without complementary price shifts—some combination of a substantial increase in carbon offsets or steep decreases in AJF costs.

CONCLUSION AND POLICY RECOMMENDATIONS

Currently, AJF penetration in North America is extremely low relative to the road sector. Because of the high expense of AJFs relative to the low projected cost of offsets in the near future, it is likely that CORSIA alone will be insufficient to induce high levels of fuel switching. The plan's delayed transition from collective, industry average to individual offset responsibility greatly reduces the incentive for any individual airline to rely on AJFs to mitigate emissions, particularly in the early years.

Estimates of the value signal of CORSIA suggest that direct offsetting costs are unlikely to exceed 5% of fuel costs by 2035 without substantially higher offset prices. Robust policy support would be necessary to spur AJF deployment at the scale needed to make a substantial contribution to CORSIA commitments. ICAO has acknowledged this reality, emphasizing a "coordinated approach in national administrations for policy actions and investment" to advance the deployment of AJFs at the member-state level (ICAO, 2016). This presents a valuable opportunity to policymakers to guide deployment toward the lowest carbon fuels at the outset before significant investments are made in higher carbon alternatives.

Canada's proposed Clean Fuels Program provides a solid foundation for incentivizing the most effective AJFs because it uses an LCFS structure that rewards fuels in proportion to their carbon intensity. However, an LCFS alone may be insufficient to stimulate the deployment of the AJFs for two key reasons: (a) other sectors, such as road transport, may be willing to pay more for limited feedstocks than the aviation sector, thus crowding it out; and (b) an LCFS may encourage the deployment of food-based AJF that can be produced at a lower price in the short term but offers low carbon savings over the long run. An "opt-in" clause for jet fuels could benefit AJF producers with LCFS credits without implementing a carbon-intensity target for the aviation sector, thus providing the industry with some of the benefits of the program. This alone would likely not level the playing field, because the road sector's demand and willingness to pay would still outcompete aviation. Therefore, it may be necessary to introduce a supplementary policy that sets aside some support solely for low-carbon fuels in the aviation sector. A blending mandate or other aviation sector–specific target would help to create a market for AJFs in the absence of a strong value signal from CORSIA.

To ensure that fuel switching generates meaningful GHG reductions, aviation fuels policy must be designed based on accurate life-cycle accounting. Comparative life-cycle assessments indicate that there are strong differences in GHG reductions from different alternative fuel pathways. In particular, AJFs derived from food-based feedstocks are associated with substantial ILUC emissions, which undermines their ability to reduce aviation emissions. To effectively drive GHG reductions, policies must account for indirect emissions or exclude feedstocks with high ILUC emissions. Strong sustainability criteria that exclude the use of high-carbon land and recommend maximum sustainable harvest rates for agricultural and forest residues would further reduce indirect emissions.

North America has a higher potential for the domestic production of sustainable, low-carbon AJF than do other world regions because of its available resources. However, despite this, and based on projections from ICAO that depict AJFs as the largest contributor to ensuring carbon-neutral growth after 2020, it is unlikely that fuel switching alone can make the necessary reductions in North America without very strong policy support. The fuel pathways that can supply the steepest GHG reductions are constrained by feedstock availability, cost, and time it would take to commercialize an advanced AJF industry. In addition, using these feedstocks in AJF may reduce opportunities to abate emissions in other economic sectors, such as the heavy-duty road sector. Considering these challenges, it is likely that the bulk of aviation emissions reductions will be achieved through carbon offsets and efficiency improvements.

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