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Aviation Fuels – Exploring Low Carbon Options Under Current Policy

Authors

Witcover, Julie, PhD
Murphy, Colin W, PhD

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Aviation Fuels – Exploring Low Carbon Options Under Current Policy

Julie Witcover, Ph.D., Assistant Project Scientist, UC Davis Policy Institute for Energy, Environment, and the Economy, University of California, Davis

Colin Murphy, Ph.D, Deputy Director, UC Davis Policy Institute for Energy, Environment, and the Economy, University of California, Davis

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16. Abstract

This paper reviews literature on technological, market, and policy factors affecting the growth of alternative aviation fuels. At present, they represent a minimal fraction of global aviation fuel used but are a critical tool for lowering GHG emissions from aviation. Even with electric and hydrogen power, substantial volumes of low-carbon liquid fuels are likely needed; these will draw heavily on biomass. Beyond hydroprocessed esters and fatty acid (HEFA) fuels, technologies, including lower carbon e-fuels, remain pre-commercial. More jurisdictions are providing incentives for alternative aviation fuel, and some on-road biofuels may be redirected towards aviation in a favorable market, because production processes for these fuels overlap. Biomass feedstocks at different demand levels need to be sourced and evaluated for unintended impacts. Research suggests alternative aviation fuels improve air quality impacts compared to conventional jet fuel. Key uncertainties in scaling alternative jet fuel remain, including ongoing concerns about land use change from biofuels, how to right-size incentives with no technology clearly dominant, what the long-term carbon budget is for aviation, and how to build fuel delivery infrastructure.

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Disclaimer

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Glossary

AJF	alternative jet fuel
ASTM	American Society for Testing and Materials
ATJ	alcohol-to-jet
CI	carbon intensity
CORSIA	Carbon Offsetting Scheme for International Aviation
CSS	carbon capture and sequestration
F-T	Fischer-Tropsch
GHG	greenhouse gas
HEFA	hydroprocessed esters and fatty acids
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
ILUC	indirect land use change
LCFS	Low Carbon Fuel Standard
Mt	megatonne (million metric ton)
SAF	sustainable aviation fuel
SIP	synthesized isoparaffins

Executive Summary

Executive Summary

Low-carbon fuels are seen as the primary tool for lowering GHG emissions from the aviation sector. However, they currently account for an extremely small fraction—less than one percent—of total global aviation fuel use. In addition to lowering GHG emissions, alternative aviation fuels may have fewer air quality impacts than conventional jet fuel. Over the last decade, several jurisdictions have adopted incentives to promote the use of alternative aviation fuels. These have increased the pace of deployment. This paper discusses important technological, market, and policy factors relevant to the growth of alternative aviation fuels, and it outlines key findings and uncertainties that policymakers and stakeholders should be aware of as they make decisions in this area.

While there is a role for electricity and hydrogen as aviation fuel, low-carbon liquid fuels are expected to be required at substantial volumes well into the century, due to the need for high energy density. Most technologies for low-carbon liquid aviation fuels remain pre-commercial, except for hydroprocessed esters and fatty acid (HEFA) fuels, which at larger scales can carry a risk of contributing to undesirable land use change. More research and development are needed to lower costs of advanced, low-carbon technologies and see them commercialized. “E-fuels” made by chemical synthesis of captured carbon using renewable electricity may be a solution but have yet to be demonstrated at commercial scale. Protocols for feedstock sourcing and robust evaluation for land use risk at different demand levels are urgently needed. Some alternative aviation fuels share production processes with on-road fuels in use—like HEFA biofuels. The overlap makes redirection of some on-road biofuels to aviation possible, under some market conditions, however currently commercialized biofuel production systems lack a pathway to achieve zero or near-zero carbon emissions.

For policymakers and stakeholders creating strategies to scale alternative jet fuel, key uncertainties remain. Right-sizing support for alternative aviation fuel presents challenges, given the lack of a clear “best” technology likely to dominate long-run alternative aviation fuel supply and, for biofuels, risk of land use change. Policy guardrails to mitigate the risk of overreliance on crop-based fuel production and ways to reliably gauge overreliance remain elusive. Intersectoral competition—among transport modes, for example, or between transport and other bioindustry—for a limited amount of biomass feedstock presents another challenge. Airport fueling system safety and space requirements make planning infrastructure build-out another key challenge. Other uncertainties remain as well: the timing of availability and range of zero-emission aircraft; the timing and GHG emission reductions of operational improvements or more efficient aircraft; the effectiveness of policy instruments, either through international bodies or at national levels; the appropriate role, if any, for carbon offsets; and, improved estimates of what carbon budget may be available to aviation over the long run.

Contents

Introduction

Aviation is widely considered to be the most difficult transportation mode to decarbonize. Consuming about 23 billion gallons of jet fuel per year in the U.S. and over 100 billion gallons globally, aviation accounts for between 2% and 3% of global greenhouse gas (GHG) emissions and is projected to grow more rapidly than other forms of transportation, with a recent industry estimate of passenger growth of 3.5% annually through 2040 (US EIA 2022; Bauen et al. 2020). The International Civil Aviation Organization (ICAO) set an aspirational goal for net-zero carbon emissions by 2050 from international aviation in its Fall 2022 assembly. While electrification continues to make in-roads beyond light-duty into medium- and specific heavy-duty ground-based applications, both batteries and hydrogen fuel cell technologies have limited prospects in aviation. The International Energy Agency (IEA) projects the scope of potential battery-electric and hydrogen fuel-cell aviation as limited to trips less than 1,000 miles, which represent no more than 30% of total aviation fuel use. Hydrogen combustion offers a possibility for about double the range and an additional 20% of fuel (IEA 2022a). Non-fuel possibilities for lowering aviation carbon emissions include aircraft/engine efficiency improvements or routing and system efficiency improvements. Additionally, increasing load factors (the fraction of seats occupied on a given flight) or better integration of aviation with ground-based transportation, such as rail, can help reduce the emissions from transportation activity currently provided by aircraft. But more is needed.

In short, at present, there is no likely alternative for energy-dense liquid fuels for the aircraft and flights that generate most aviation emissions. Current aviation decarbonization strategies rely heavily on carbon offsets, but these are at best a temporary solution. Moreover, offset programs have struggled so far with a variety of challenges relating to accounting, additionality,[1] verification, and permanence. With substantial projected increases in long-distance air travel this century, finding ways to displace fossil jet fuel to meet climate goals is urgent.

The development of low carbon aviation fuels that can be used with current aircraft and aviation infrastructure is well underway.[2] Several technologies/conversion processes have received ASTM certification at specified blends in jet fuel.[3] Commercial use has begun, albeit at low volumes. High costs continue to limit expansion, especially for the fuels with the lowest carbon content. However, aviation provided a bright spot for low-carbon fuel development in the 2010s, with global production of alternative jet fuel rising to over 20 million gallons (Wildes 2022) and perhaps as much as 80 million

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[1] *Additionality* refers to assessing that a GHG reduction would not have occurred in the absence of a policy, in this case the offset program.

[2] The term 'sustainable aviation fuel' (or SAF) is sometimes applied to all alternative jet fuel (AJF). However, not all AJF need be low carbon, or sustainably produced (a concept that is difficult to clearly define and apply, and thus subject to misconception). Indeed, for all feedstocks, and especially crop-based ones, the particularities of sourcing and production can lead to higher carbon and other undesirable outcomes.

[3] ASTM stands for American Society for Testing and Materials, which develops production and testing standards for jet fuel, among other industries.

gallons (IATA 2022) per year in 2022, even as cellulosic biofuels failed to emerge, as had been hoped for on-road applications.

An array of private sector advocates for alternative aviation emerged—investment, financing, and off-take agreements[4] lined up. Also, more attention was paid to cellulosic feedstock that is sourced in ways to minimize land use competition, an issue with conventional biofuel crops and energy crops grown on land suitable for foodcrops (Witcover and Williams 2018). Indeed, most of the existing cellulosic low-carbon fuel initiatives pivoted from on-road to aviation applications.

The focus on aviation as an outlet for non-petroleum liquid fuels—biofuels and other synthetic fuels—has only increased since the 2010s, likely due to expectations of a long-term need. A recent ICAO report pointed to low-carbon alternative aviation fuel as the approach with the greatest potential to reduce GHG emissions from the sector, projected as capable of achieving approximately two-thirds of needed reductions. Figure 1 depicts projected CO_2 emissions to 2070 in international aviation without any mitigation measures (business-as-usual, top line), reductions in CO_2 emissions ("wedges") from several approaches including SAF, and residual emissions (bottom "wedge") if all these steps were implemented and performed in line with projections (ICAO 2022d). The result would leave just over 200 megatonnes[5] of CO_2 ($MtCO_2$) of residual international aviation emissions in 2050, roughly one-third of 2019 levels. This accounting, however, assumes several conditions favorable for assessing a low GHG emissions profile of the fuels.[6] If these assumptions do not match actual future development, then better performance from biomass-based fuels or other savings categories would be needed.

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[4] Off-take agreements refer to contracts for placement of particular volumes of fuel yet to be produced.

[5] One megatonne is one million metric tons.

[6] Among the assumptions are sufficient land availability and greater agricultural productivity that allow for more reliance on crop-based feedstocks (ICAO 2016). ICAO also assesses emissions from land use changes (an estimate with tremendous uncertainty, as will be discussed later) using the average or the lower of two estimates from alternative models, and they allow mitigating behaviors to waive accounting of ILUC emissions (ICAO 2022c; 2022b). Very low carbon fuels, like those needed to achieve deep GHG reductions from aviation, likely require either extremely low-carbon advanced fuels made from non-crop feedstocks—such as e-fuels made using zero-carbon electricity—or biofuels with carbon intensity much lower than any that have yet been produced at commercial scale.

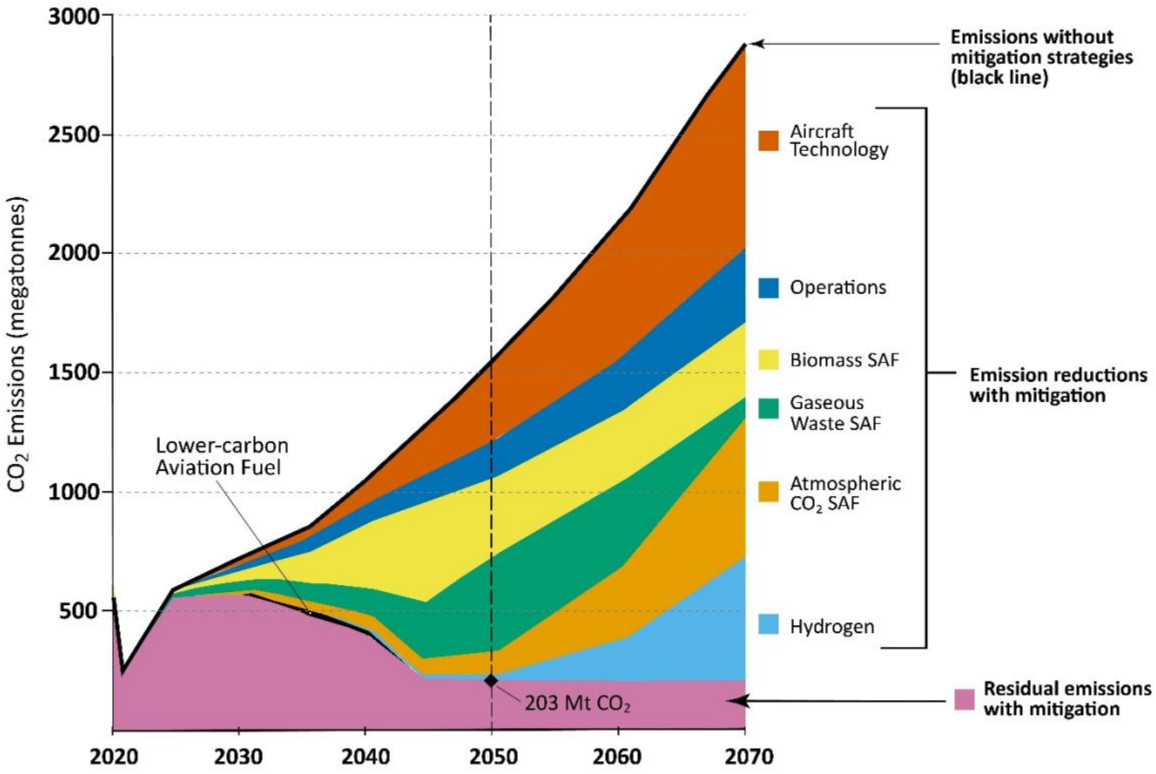

Figure 1. ICAO Long-Term Global Aspirational Goal: Projected international aviation emissions without mitigation strategies ("business-as-usual") and potential emissions reductions from mitigation measures by source (top "wedges") and remaining (residual) emissions after mitigation measures. (This projection is based on an assumption that aircraft technology advancements after 2050 do not contribute further to emissions reductions.) Adapted from the most ambitious savings scenario. (SAF, sustainable aviation fuel; Mt, megatonne, or million metric ton)(ICAO 2022d).

The rising interest in low-carbon alternative jet fuel has been marked by a proliferation of announced goals by airports, airlines, and jurisdictions to ramp up production and use starting in the 2020s and growing from there. Moreover, while policy support for alternative aviation fuels remained modest in the 2010s, that is changing as more jurisdictions begin to act in this area, including not just the industry entity ICAO, but also the EU, the US, the UK, and states such as California.

It is critical for policymakers and business stakeholders to understand the extent to which current initiatives can meet ambitious stated goals and how best to harmonize efforts to simultaneously decarbonize the aviation and on-road transportation sectors (especially heavy duty). This paper reviews the status of alternative aviation fuels today,[7] and then it explores key developments related to technology and policy in separate sections. It also touches on issues related to the transition to low carbon aviation fuels, given today's realities, and provides conclusions.

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[7] Hydrogen is sometimes proposed as an alternative aviation fuel, either converted to electricity in a fuel cell or combusted in a turbine. Because the technologies and infrastructure needed to support hydrogen aircraft are still far from commercialization, hydrogen is less discussed in this paper.

Fuel Technologies

Nine alternative jet fuel conversion processes have received ASTM certification thus far that make them eligible for use in commercial aviation (ICAO 2022a). Still, alternative jet fuel technologies face considerable hurdles to be competitive in the marketplace and none have yet demonstrated the capacity to scale sufficiently to meet global aviation fuel demand. Global energy demand for aviation fell dramatically in 2020 at the start of the pandemic but is projected to rebound to 2019 levels of close to 100 billion gallons annually sometime in the 2020s. Recent projections for later periods see a global aviation demand of around 135 billion gallons (jet fuel equivalent) in 2040, and 154 billion gallons by 2050, about 20% of this from domestic U.S. demand (Merchant, Kent, and Lewis 2022). By contrast, offtake agreements for alternate jet fuel (AJF) now total about 10.5 billion gallons spread over many years, a significant fraction of this amount is expected to come from facilities that have yet to be built (ICAO 2022e).

All currently certified technologies require some blending with conventional jet fuel to earn the ASTM certification. Five technologies are certified at up to a 50% by volume blend, and the others to 10% or less. Of the certified technologies, hydroprocessed esters and fatty acids (HEFA)—from used cooking oil, animal fat, or vegetable oils as feedstock—has provided virtually all alternative jet fuel in the marketplace to date, and only HEFA has demonstrated an ability to scale commercially. However, global feedstock production for this process has not demonstrated a commensurate capacity to sustainably scale. While the HEFA process can use wastes and residues, such as used cooking oil, or tallow from meat processing, these sources of feedstock have largely already been tapped for biofuel production and represent only a small fraction of global aviation fuel demand. Further growth of HEFA fuels will likely come from crop-based vegetable oils, which require significant amounts of land and fertilizer to be grown at commercial scale. A second process, Fischer-Tropsch (F-T) synthesis, creates synthetic hydrocarbons from carbon monoxide and hydrogen. These have historically been produced by gasifying organic matter, fossil fuels, or plastic as a source of feedstock. E-fuel production typically employs F-T synthesis but uses carbon obtained by splitting CO_2 captured from waste sources or extracted from ambient air and hydrogen produced by electrolysis of water.[8]

E-fuel synthesis requires substantial amounts of electricity, due to the high energy demands associated with splitting CO_2 and water to produce carbon monoxide and hydrogen, respectively. E-fuels made from electricity generated from fossil sources offer little, if any GHG benefit. Using electricity from zero-carbon sources can yield aviation fuels with near-zero life cycle GHG impacts. Electric grids in most jurisdictions, however, still rely on fossil fuels for a significant fraction of their generation and, in most cases, using new renewable energy capacity to displace existing fossil fuel plants yields greater net GHG benefits than using it to produce e-fuels that displace petroleum fuels. As electrical grids

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[8] For more on these technologies, see a literature review performed for the EU Clean Sky 2 Joint Undertaking (van Muijden et al. 2021). Also see (Bauen et al. 2020).

transition away from fossil fuels, toward a greater reliance on zero-carbon electricity, the GHG benefits of e-fuels will be enhanced.

For fuels made by F-T synthesis of carbon and hydrogen obtained from gasification of solid matter, the greatest GHG benefits and accordingly the greatest amount of interest at present, come when organic waste or agricultural residues are the primary feedstock. A pioneer plant that uses gasification of municipal solid waste to an intermediate bio-oil using F-T synthesis just began commercial production after considerable delays, however it has yet to produce at its rated capacity. Additional plants using a similar process are planned, for a total production capacity of close to 400 million gallons of AJF per year (Fulcrum Bioenergy, Inc. 2023). Another company's pioneer plant that would use the same process recently went into foreclosure after facing repeated delays from technical and financial challenges (Sickinger 2023).

Conversion of biomass ethanol to jet fuel (alcohol-to-jet, or ATJ) has also seen considerable commercial interest. LanzaJet has begun construction of the first plant, in Georgia, and plans to begin production in 2023 with feedstocks including, but presumably not limited to, waste-based sources (Lanzajet 2022). Additional plants are planned. Gevo has also announced plans to build several ATJ plants over the next several years (Wildes 2022). The success of these pioneer plants—e.g., reaching production at intended capacity with few delays and cost overruns—constitutes a critical milestone for future investment. Cellulosic biofuel technology has historically struggled with this step; many cellulosic biofuel plants in the 2010s failed due to technical and financial challenges as well as perceived policy instability (Witcover and Williams 2018). The near-term AJF pathways undergoing commercialization—HEFA, F-T, and ATJ—all use production processes that also yield renewable diesel suitable for on-road use, as well as light-end products, such as naphtha and propane.[9] Optimizing the production of AJF generally cuts into renewable diesel share, with light ends also increasing (Pavlenko, Searle, and Christensen 2019). We return to the question of competition across transport modes for low carbon fuels in the next section.

Beyond those receiving most commercial attention now, the list of potential AJF technologies actively being explored is long. It includes fast pyrolysis of biomass—a technology with several failed efforts to enter the transport fuel market in the 2010s—as well as direct sugar to hydrocarbons (or synthesized isoparaffins), or hydrothermal liquefaction of biomass. While there is still no consensus about which of these will be successfully developed at competitive costs, economic assessments agree that all AJFs are currently too expensive for ready market entry without significant policy incentives. These assessments generally find that AJF costs are around two to five times that of conventional jet fuel (Bauen et al. 2020).

Among the AJF pathways assessed, biofuels had the lowest production costs, which is not surprising given their current commercial dominance. For the biofuels evaluated, HEFA is the least expensive,

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[9] Light-end products are hydrocarbons (liquids and gases) that accumulate at the top of distillation towers during refining.

followed by F-T and ATJ (Pavlenko, Searle, and Christensen 2019).[10] However, cost rankings are highly sensitive to feedstock costs, which have tended to rise over time for biofuels as biomass resources come more in demand for energy and other uses. Low carbon e-fuels (and hydrogen, which is not considered here) currently face higher costs and rely for future cost competitiveness on availability of inexpensive low carbon electricity, as well as cost savings from technological improvement. Cost savings in the future may be greater for e-fuels than for biofuels, because e-fuels have been less researched to date, and biofuels have a cost profile inexorably linked to agricultural production costs (van Muijden et al. 2021).

Beyond cost, the factor most influencing the potential for specific AJF pathways is current and expected future carbon-lowering potential. Estimates of life cycle carbon intensity (CI)—an assessment of GHGs emitted over the entire supply and distribution chains, from feedstock production through final fuel use—are commonly used for this purpose.[11] In most biofuel systems, production of biomass feedstock is the largest contributor to the fuel's life cycle GHG emissions. This includes the fertilizer, energy, and transportation inputs to agriculture, as well as indirect impacts that occur when biofuel production significantly affects existing agricultural markets. For example, many biofuels have estimated GHG emissions from indirect land use change (ILUC). This reflects competition for arable land between food, feed, industrial, and biofuel crops. When biofuel production consumes a crop that would otherwise have been used elsewhere, it increases market pressures to bring more land into agricultural production to replace what was lost. This additional land conversion, essentially caused by the increased aggregate demand for agricultural products, can entail significant GHG emissions.

Fuels derived from crop, and especially rowcrop, feedstocks, such as HEFA AJF from soy and ATJ from corn, are estimated to have a higher CI score than waste or cellulosic fuels due to ILUC, since the demand for starch or oil consumed by the biofuel process will tend to stimulate new supply. There is some potential to substantially decrease fuels' CI scores via carbon-saving measures, especially carbon capture and sequestration (CCS). For the lowest carbon assessment, non-crop biomass (such as municipal solid waste, agricultural residues, residue oils, or waste wood) and energy crops grown under certain circumstances may create much less ILUC risk. Where residues or energy crops are used, sustainable sourcing protocols are needed to ensure low CI scores. These include leaving sufficient agricultural residue to protect soil productivity, growing perennial grasses with low fertilizer input on marginal land not suitable for other cropping, and ensuring feedstocks are not being diverted from existing uses that then would require use of more land-reliant products.[12] E-fuels (and hydrogen),

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[10] The paper reports its results are in line with other cost estimate analyses.

[11] CI score is central to policy incentives for alternative transport fuel in programs such as the Low Carbon Fuel Standard in California, and it is also used more broadly, including in assessments of alternative jet fuel for ICAO targets.

[12] This can occur, for example if diverted oils are backfilled by additional demand for a fuel that has substantial ILUC effects, such as palm oil. As yet the regulatory systems do not include an assessment of this indirect pathway to increased GHG emissions for feedstocks. For an assessment of biofuel AJF feedstock risk (Pavlenko

because of their potential to be made from near-zero carbon sources like solar- or wind-generated electricity, have a clearer path to much lower carbon footprints, although they could also be made using biomass and be subject to the same sourcing protocols described above.

ILUC assessments are uncertain and variable and expected to remain so. That said, ILUC emissions per unit of fuel produced would be expected to increase as use of biomass scales without other mitigations. This is in part because normal market pressures would tend to locate existing production on the best possible land for production, so additional production would tend to go on less and less productive land over time, increasing the amount of land, and thereby the likely GHG impact for each additional unit of production. Because some of this additional land has higher carbon sequestered in it, which is released upon conversion, it can have high GHG emissions even if not much land is involved. For these reasons, the aviation industry has placed more emphasis on using bioenergy from waste sources, although these feedstocks are not expected to scale to a level implied by demand for jet fuel (Merchant, Kent, and Lewis 2022). Indeed, "biomass-SAF" in the ICAO Long Term Aspirational Goal assessment (see Figure 1) includes crop-based sources, as described above.

Substantial GHG emissions from ILUC remain a real and problematic risk, despite some ILUC risk mitigation provisions in fuel policies across multiple jurisdictions. These provisions typically fall into one of several categories. One is feedstock sourcing guidelines, as have been adopted by the EU's Renewable Energy Directive II and Canada's Clean Fuel Regulations. These specify conditions for obtaining eligible feedstock and exclude from eligibility those deemed to be high-ILUC risk. Well-designed feedstock guidelines can reduce the risk of problematic feedstocks entering a jurisdiction's fuel market but offer little protection against the indirect, market-mediated risk of ILUC. They also do little, if anything, to safeguard against feedstock providers selectively channeling highly sustainable feedstock to fuel markets and expanding cultivated land area for crops that would go to less-regulated markets. A second common method of ILUC risk mitigation is the use of ILUC charges assigned to feedstocks that drive market-mediated pressures for land expansion. This approach is in effect in California's Low Carbon Fuel Standard (LCFS) and similar programs in Oregon and Washington, as well as under the U.S. Renewable Fuel Standard. ILUC emission estimates can, in theory, account for ILUC impacts in a reasonable way, but doing so in practice requires modeling at a level of precision that has not been demonstrated to date. As a result, current ILUC charges are based on estimates with a wide uncertainty range. Finally, some jurisdictions cap the use of certain feedstocks for eligibility in their alternative fuel programs, such as the EU's share limits on food and feed crops in its Renewable Energy Directive II, and the U.S.'s volume limit on corn starch ethanol in its Renewable Fuel Standard.

Several of the AJF technologies with technological readiness levels closest to commercialization, and with lowest current cost assessments, build off existing, prevalent, and well understood biofuel technologies—HEFA renewable diesel and ATJ. HEFA renewable diesel has HEFA AJF as a coproduct that the production process can be optimized for to increase its proportion of the final product slate,

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and Searle 2021). Excessive land competition can have other undesired consequences, like higher food prices or lost ecosystem services.

and ATJ uses ethanol as a feedstock. The F-T process using municipal solid waste, if successful, would open the door to lower carbon AJF using cellulosic feedstocks at considerable scale. Additional climate impacts from the use of AJF—for example, on contrail formation and persistence—are still being explored and deserve consideration in assessing the climate impact of AJFs.

Other factors that impact the attractiveness of potential AJFs include usability with existing fuel delivery and infrastructure, as well as air quality impacts. Of ASTM-certified AJFs, none can yet be the sole drop-in fuel for jet travel, and only one, catalytic hydrothermolysis jet fuel (which uses oil feedstocks similar to HEFA) has a clear pathway to 100% use as jet fuel (Kramer et al. 2022). AJFs requiring blends for use in current jet aircraft could also have characteristics that necessitate blending for use in delivery and storage infrastructure or separate handling if used at higher blend rates. Electricity and hydrogen require innovations in aircraft before they can deliver on their potential for a portion of aviation use, as well as extensive investments in fueling infrastructure at airports.

Like most non-petroleum alternative fuels, AJFs generally reduce non-GHG air pollutant emissions when they displace conventional petroleum jet fuel. A 2022 study evaluated the air quality benefits from large-scale adoption of alternative aviation fuel across the U.S. and found them to be largely due to the lower sulfur content of the fuel and its ability to reduce particulate (soot) emissions from aircraft during landing and takeoff (Arter et al. 2022). Further research is needed to better understand impacts across the full life cycle of such fuels, particularly to understand whether changes in emissions from fuel processing or increased demand for hydrogen compared to petroleum might erode the air quality benefits from consumption. In addition, use of feedstocks in AJF rather than on-road renewable fuels can present trade-offs as regards air quality (among other areas), for example in producing HEFA AJF rather than renewable diesel. Since both fuels use lipid feedstocks, like vegetable or waste oils, and are produced by hydrotreatment, it is likely that near-term growth in HEFA AJF would come at the expense of further growth in renewable diesel. Current assessments of the GHG impacts of the fuels are generally comparable, and while renewable diesel provides air quality benefits when burned in older (pre-2010 model year) diesel engines, as these retire out of the fleet, the potential air quality benefit declines (Murphy et al. 2022). This implies that a switch from renewable diesel production to HEFA AJF could yield air quality benefits, especially as the prevalence of older diesel engines declines. We return to cross-sectoral topics (like the trade-offs between on-road and aviation fuels) in the next section.

Given the challenges facing low-carbon AJF, ranging from ensuring low carbon feedstock sourcing to developing novel technologies deployable at competitive costs, current policy efforts seem inadequate. If all national AJF blending targets now in place globally were met in 2050, the implied demand would be about 16 billion gallons by 2050, less than 15% of projected total aviation fuel demand (Dimitriadou and Lavinsky 2022).

Transition Issues

Transitioning to a reality that incorporates AJF at scale in aviation alongside continuing decarbonization in other sectors of transport and the economy presents daunting challenges. Development of affordable low-carbon AJF, discussed above, is moving forward, but the goal of displacing all or even a majority of global jet fuel is still out of reach. Scaling production of AJF, especially using biomass, risks sacrificing low-carbon attributes, as discussed above. In addition, while e-fuels can theoretically scale to meet future need, their GHG benefits may be limited until global electrical grids have transitioned to a predominantly zero-carbon electricity supply. Policy structures to safeguard against high-emission outcomes remain inadequate, especially where ILUC is concerned. Building off existing infrastructure and technologies can lower costs, prevent asset-stranding, and make near-term changes more accessible. On the other hand, making large investments in newer systems designed with near-zero carbon economy in mind carries higher risks given unproven systems but also carries higher potential GHG emission savings earlier, and potential for technological and other learning that will help achieve a lower carbon economy.

The transition to near-zero carbon aviation poses additional trade-offs over how to allocate resources. These include decisions over which of multiple potential fuel technologies might use a given feedstock (and how much), and which of multiple potential transport sectors might use a given fuel. Aviation may compete not only with on-road uses, but also maritime applications, which, like aviation, are likely to need energy-dense fuels beyond what electrification can supply. More information is needed to guide such resource decisions. In addition, economies of scale or scope, or other logistical or market security benefits, might flow from using similar or identical conversion technologies in multiple transport or other sectors (e.g., if hydrogen is used more broadly throughout the economy). Such broad applications could shift cost assessments based on use in a single sector alone. Particularities of each fuel use sector—such as fuel delivery systems, blending potential, and/or spatial distribution of production or demand centers—might argue for or against such an overlapping use of fuels, or favor use of one sector over another. Policy makers must balance the economies of scale and fungibility benefits of emphasizing a few, or even one, ubiquitous fuels against the value of flexibility and competition that would come with a more diverse portfolio.

Timing differences in likely transitions across sectors may also influence strategic cross-sectoral decisions. The example mentioned in the previous section provides an example: HEFA fuels used in aviation can carry air quality benefits that are lost in on-road heavy-duty fleets as they shift to newer vehicles with more efficient internal combustion engines or other powertrains. Maximizing the air quality impact of HEFA fuels may mean preferentially directing them toward on-road applications until the on-road fleet is made up of newer vehicles that derive no benefit from renewable diesel, then shifting incentives to encourage HEFA fuels to enter the aviation sector, where modest benefits will persist for several decades at least. Timing of sectoral use may also influence the ability of a technology to commercialize and scale, after which it could be incentivized to deploy in another sector. Existing policies better target commercial deployment and scaling of technology-ready low carbon technologies on-road, as evidenced by the meteoric rise of renewable diesel in California and other jurisdictions with LCFS programs (Mazzone, Witcover, and Murphy 2021). If newer very-low-carbon technologies using waste or cellulosic fuels were developed, on-road scale-up would fill a persistent need for the next few decades, given the time it will take to convert heavy-duty fleets to electric or fuel cell vehicles where those are feasible. In contrast, because biofuel use in aviation is foreseen as an eventual need, there is momentum to better prioritize its use in that sector, to begin that transition and uncover potential hurdles that might not otherwise be apparent. In addition, the market for aviation has sparked more of the players—who are needed to successfully develop and commercialize emerging fuels—to act. These players include investors, producers, end users like commercial and government/military entities, as well as airports. Interest in aviation has motivated pioneering work to commercially produce and distribute the lowest carbon liquid fuels, such as the above-mentioned HEFA AJF and ATJ products that use waste-based feedstocks. Given the long-run demand for liquid fuels in aviation, AJF is likely to be the fuel that takes on the challenges posed by lower-carbon cellulosic fuels, after over a decade of failures. Even after the economy has electrified and thus largely reduced its dependence on liquid fuels, demand for many billions of gallons of AJF will remain.

The end use for more conventional biofuel technologies during a transition is also under discussion. If ATJ scales in a way that builds off HEFA renewable diesel and corn ethanol without additional safeguards against land conversion impacts, the result could be undesired additional GHG emissions and other consequences via impacts on food markets and ecosystems, as well as over-investment in and prolonged reliance on technologies that seemingly have limited potential to achieve low carbon goals. At the same time, as on-road demand for ethanol declines due to the shift to electric vehicles, the production capacity and supply chains built to produce ethanol for gasoline blending could be readily converted to ATJ production, which would preserve the value of existing investments, maintain stable agricultural commodity markets, and sidestep a potential political fight to remove existing incentives, such as those currently implemented via the U.S. the Renewable Fuel Standard (RFS). This could be a beneficial use of existing assets if there were assurances and safeguards that fuels using conventional row crops can result in carbon savings, along with clear incentives to lower carbon fuels' use in aviation. Deployment of CCS at ethanol production facilities may offer additional relatively low-cost GHG reductions.

For some of these apparent trade-offs, a clear path has yet to emerge, and there are likely opportunities to manage portfolios of risk/reward that will require more discussion and study to navigate. Critical to the discussion is the extent to which the market signal can continue to be harnessed as new technologies are developed and tried. Policies that build in some mechanism for lowering costs and improving feasibility under extant market conditions, including levels of consumer acceptance, will increase the likelihood of the eventual successful rollout of low-carbon technologies. AJF emerged in the 2010s as a potential catalyst to drive development of very low carbon hydrocarbons when efforts targeting on-road applications failed, however, it is the policy environment, to which we turn next, that holds the key to whether that potential plays out.

Alternative Aviation Fuel Policy Landscape

Policies to support alternative aviation fuel are complex due to overlapping jurisdictional boundaries, complex ownership, and contractual structures in the aviation sector, and the overriding sectoral emphasis on safety. International aviation is governed by a policy structure first established under the 1944 Convention on International Civilian Aviation, also known as the Chicago Convention. This established the International Civilian Aviation Organization (ICAO) as the primary governing body for issues related to international aviation, and it restricts nations or other jurisdictions from most forms of regulation (other than safety) over international aviation. In practice, the Chicago Convention largely prevents jurisdictions from imposing fuel taxes, environmental fees, or other emission-reducing policies that affect international aviation.[13] ICAO member states, which include almost every nation in the world, are allowed more flexibility in regulating flights and emissions at the national level, or among select multi-national jurisdictional structures, such as the EU, which can largely regulate flights within the EU with similar authority to that of a nation.

International efforts to reduce emissions have largely centered on the Carbon Offsetting Scheme for International Aviation (CORSIA). First adopted by ICAO in 2016, CORSIA proposes actions that would hold net international aviation emissions at their 2020 level and reduce them to half of their 2005 baseline by 2050. While CORSIA includes targets and coordination to increase aircraft efficiency and find additional savings through operational improvements, the majority of emissions cuts come from carbon offsets and increasing the supply of alternative aviation fuels. Offsets have attracted significant criticism from many environmental and equity-focused groups and scholars, and they suffer from a number of challenges related to verification, additionality, and permanence. CORSIA's approach to alternative fuels requires only a 10% reduction in life cycle GHG impacts to qualify and has only minimal protection against biofuel-driven ILUC. As first implemented, CORSIA had few mechanisms to promote lower-carbon or more sustainable types of fuel over higher-carbon ones, instead it set an overall GHG target and relies on offsets to provide the bulk of nominal GHG reductions. Over time, and in response to criticism from a variety of stakeholders, the GHG reduction potential of AJF has been improved, in part by the development of more effective protocols for AJF carbon intensity assessment, and stronger commitments by participants to meet deep decarbonization targets.

Within the U.S., states can be granted broad authority to set fuel standards or emission policies. However, federal authority preempts most state regulatory exercise over interstate domestic flights, which make up the overwhelming majority of domestic aviation in the U.S. California enjoys special regulatory flexibility to set its own energy and emissions policies due to its special status under the Federal Clean Air Act and subsequent amendments, as well as its own state GHG reduction policies.

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[13] The fragmented jurisdictional structure also complicates data collection and comparison. Since fuel used for international purposes, or by international carriers, is regulated and taxed differently, no readily available sources compile a comprehensive set of data on fuel consumption for both domestic and international uses.

Because of California's large size and the presence of multiple major population centers, intra-state aviation represents a non-trivial source of fuel consumption and associated emissions. Approximately 400 to 500 million gallons of jet fuel were consumed on intra-state flights in 2019.[14,15]

Because of the complex and fragmented jurisdictional scope of authority over aviation fuels, most policies relating to emissions from aviation fuels have, to date, been focused on incentives or voluntary agreements. U.S. federal policy has historically been limited to volumetric tax credits and R&D subsidies for advanced aviation and fuel technologies, although alternative jet fuel has opt-in status to generate compliance credits in the Renewable Fuel Standard. As part of a broad climate and energy package, the Biden Administration has announced the Sustainable Aviation Fuel Grand Challenge, which provides a full portfolio of policy measures, including:

- An aspirational target for carbon neutrality by 2050, with an interim target of 3 billion gallons of domestically produced alternative aviation fuel by 2030.
- Volumetric tax credits for aviation fuel that achieves at least a 50% GHG reduction over its full life cycle compared to conventional, with an additional per-gallon subsidy tied to further reductions in GHG emissions.
- $3 billion in loan guarantees and other support for the construction of alternative aviation fuel production capacity.
- Increased R&D support for technologies that can reduce the fuel consumption of commercial aircraft.
- Investment and regulatory support for improvements in scheduling, routing, and air traffic control to achieve additional operational savings.
- Renewed engagement with the ICAO and CORSIA processes to build international momentum for reducing emissions.

Similar efforts have been recently adopted by the EU, through its ReFuelEU proposal. The proposal was first issued in 2021 and has subsequently gone through several rounds of consultation and amendment. It would require increasing fractions of aviation fuel used in the EU to come from alternative sources, starting at a 2% alternative aviation fuel blend rate in 2025 and reaching 63% by 2050, with a subtarget for synthetic fuels such as e-kerosene starting at 0.7% in 2030 and reaching

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[14] While airlines assert that regulation of intra-state aviation is preempted under both federal law and international treaty, the California Air Resources Board has determined that intra-state aviation fuel can be regulated by a state. This paper will adopt that conclusion as a basis for policy discussion, however we stress that this paper is not a work of legal analysis and make no claims about the jurisdiction or preemption.

[15] The estimate of 400 million gallons is based on forthcoming UC-ITS Renewable and Innovative Mobility Initiative work. The estimate of close to 500 million gallons comes from a recent report (Elkind, Segal, and Lamm 2022).

28% by 2050. Alternative aviation fuels under this policy could not be made from food or feed crop sources of biomass,[16] though waste oils are allowed, at least temporarily.

Having left the EU, the UK has adopted its own portfolio of policies related to alternative aviation fuels, notably a target for 10% alternative aviation fuels in domestic use by 2030, and net-zero domestic aviation GHG emissions by 2040, with a further target for at least 5 domestic production facilities.

California is among the few U.S. states adopting policy to reduce the emissions from aviation fuels, though its impact has been limited to date. In California, AJF became eligible in 2019 to earn credits—market-traded compliance instruments with monetary value—as an opt-in fuel for the state's Low Carbon Fuel Standard (LCFS), which focuses on lowering the rated carbon intensity of the state's transportation fuels. Oregon and Washington, which have implemented fuel policies similar to the LCFS, have followed this approach. More recently, California's governor announced a goal that 20% of aviation fuel used in the state be low carbon by 2030.[17] California regulators have indicated that they are considering whether to include all aviation fuel used for intra-state activity under the LCFS, making conventional jet providers for this use an obligated party for the first time. This would add a cost to providing conventional jet for intra-state travel and increase demand for lower-carbon alternative fuels used in California—in aviation and on road—for LCFS compliance. AJF providers would benefit from the increased cost on conventional jet fuel due to the policy as well as from the value of the LCFS credits they generate.

Including aviation fuel under a program like the LCFS could follow one of two main design choices: aviation fuels could be included in the existing LCFS, which predominantly covers on-road transportation fuels, or they could be brought into a separate LCFS program governing a subset of transportation, such as all non-road fuels or just aviation. The rationale for a separate LCFS for aviation, and possibly other non-road applications, is that the set of potential lower-carbon fuels is different and more limited than those available in the on-road space, where EVs can satisfy the majority of transportation activities in a cost-effective and efficient manner. Without the potential availability of EVs for widespread adoption, and the limited supply of sustainable biofuels available, the pace of decarbonization in aviation is likely to be considerably slower than for on-road vehicles. Including aviation with on-road applications would likely imply a persistent net flow of compliance credit from on-road sectors to those generating deficits in aviation. In fact, if EV deployment is sufficiently rapid, relative to LCFS target increase, compliance obligations within the aviation sector could be met predominantly by purchasing compliance credit from on-road fuel providers. A separate LCFS focusing

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[16] Importantly, this measure bans food or feed crops regardless of whether they are the primary or a secondary ("intermediate") crop; the Renewable Energy Directive II does not explicitly exclude intermediate crops (Baldino and Mukhopadhaya 2022).

[17] It is not yet clear whether this is intended to mean 20% of fuel for intra-state travel, 20% of all fuel loaded onto aircraft in-state, or some other quantity.

on aviation would likely require a slower pace of decarbonization but could provide more certainty that such decarbonization actually occurs within aviation.

Importantly, the policy structures alone to date have proved insufficient to generate the kind of very-low-carbon *and* scalable liquid fuels that are required. Market mechanisms like the LCFS, and to some extent the Renewable Fuel Standard, have a proven ability to prompt innovations within previously existing supply chains or in technologies that make heavy use of them. Given a sustained trajectory toward higher program targets, and with high enough credit prices, these mechanisms could more strongly incentivize innovative, very-low-carbon technologies to come to market. With targets and market conditions like those that have existed to date, however, existing technologies with some improvements suffice to meet existing targets. More novel technologies, like those now being pioneered using cellulosic sources, have proven elusive under these policy structures and will likely need more concentrated attention and policy innovation, especially to help cover up-front financing difficulties and mitigate market and policy risk. Contracts-for-difference have been suggested for this purpose (Pavlenko, Searle, and Christensen 2019). These could provide a floor of support to competitively chosen pioneer projects through early production phases that help prove technologies and improve them before a jump to full scale.

Across all jurisdictions, the primary near-term aviation fuel policy challenge is the need to develop and rapidly scale up production of low-carbon alternative fuels that can meet long-term climate goals while balancing the need to reduce emissions across all sectors of transportation. Total global production of biofuels, predominantly ethanol and biodiesel, was around 46 billion gallons in 2022 (IEA 2022b). Even if most or all of this were deemed to be low in carbon and redirected to aviation, it would represent no more than half of the global aviation fuel demand, and alternatives would need to be found for all on-road applications.

Despite the urgent need for a path to rapid scale of low carbon AJF, policy must be cautious to avoid supporting unsustainable models of growth. HEFA AJF has demonstrated the capacity to rapidly grow, provided that sufficient supplies of cost-effective feedstock are available. The HEFA process, however, is dependent on lipids for feedstock, and most growth in this space is expected to come from crop-based vegetable oils, which pose a significant risk of causing GHG emissions from land use change. Some sustainable growth in vegetable oil production may be possible, such as by enhancing oilseed yields, adopting oilseed cover crops, or developing crops that can produce oil on marginal or degraded land.[18] Policy needs to strike a balance between supporting increases in HEFA AJF production capacity within limits that don't risk a strong ILUC effect. The challenge is that overly generous or poorly targeted incentives could easily support fuels that are produced from sources of oil that do trigger ILUC. Moreover, given the vast, fungible, and rather opaque international markets for vegetable oil, it is difficult for policymakers to effectively prevent market-mediated land use change through sustainability criteria alone. Even if the oils used by HEFA AJF producers fit those criteria, expanded

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[18] In order to be truly considered "additional," however, and not trigger ILUC, these efforts would have to *not* have occurred in the normal course of business (in other words, without the additional demand for aviation fuels).

demand from alternative aviation fuels could put enough pressure on vegetable oil markets to cause damaging changes in land use.

Effectively addressing this challenge will require a portfolio of policies. Sustainability requirements, such as those adopted by the EU, or requirements for biofuel feedstock to come from land that has historically been cultivated, such as those in the CORSIA fuel protocol, are insufficient to fully mitigate the risk of policy-driven land conversion. Additional measures, such as the LCFS ILUC adjustment factor, volumetric limits on fuels with high ILUC risk, or others are required to more fully contain the risk of unwanted land use change consequences.

Conclusion

Deployment of alternative aviation fuels has expanded rapidly over the last decade, however that rapid expansion was from a historical baseline of essentially zero. At present, alternative aviation fuels make up less than one percent of total global aviation fuel demand. The industry must continue to grow at an exponential rate and develop new, lower-carbon options if the aviation sector is to meet critical GHG reduction targets. This paper summarizes several key technological, market, and policy considerations related to alternative aviation fuels. This section outlines key findings and areas of uncertainty for policymakers.

Key Findings

Low carbon liquid fuels are needed for aviation to significantly reduce emissions. Zero-emission technologies, like batteries or hydrogen, may be able to power regional and short-haul flights, but medium- and long-haul flights will require the energy density of a liquid fuel for decades to come.

At present, only hydrotreated lipids, e.g., HEFA AJF, have demonstrated an ability to scale. These fuels, especially those made from low-carbon residual oils (currently rated as ~70% life cycle GHG reduction from jet fuel) likely reduce emissions from aircraft when they displace fossil fuels. The supply of residual oils without existing uses is extremely limited, however, and crop oil alternatives present risks of land use change. While there may be some growth opportunities for residual oils from untapped sources or general economic growth, they cannot reliably meet more than a small fraction of total global aviation fuel demand without risking their low-carbon profile. There may also be potential for increasing oil production using cover crops or crops on marginal land, but these approaches have not been demonstrated at scale.

Multiple technologies could potentially supply more sustainable and lower-carbon liquid fuels, but they have struggled to commercialize. Early deployment of facilities using cellulosic technologies have yet to achieve sustained production at their rated capacity. Electrofuels, synthesized from carbon and hydrogen using renewable electricity appear to have the potential for growth at scale, but efficiency, cost, and low-carbon electricity supply concerns must be addressed. Algae, energy crops, or other sources may be able to contribute but have yet to demonstrate cost-effective scalability.

It is possible for biofuels used on-road to be redirected to aviation. There are pathways for currently prevalent on-road biofuels to move to aviation. Global production of ethanol is around 30 billion gallons per year. Ethanol can be converted to jet fuel via alcohol-to-jet synthesis. Similarly, feedstocks currently used for biodiesel and renewable diesel can be readily redirected to make HEFA AJF (likely at the same conversion facility, in the case of renewable diesel). The extent to which existing biofuels should move on to pathways destined for aviation use, especially as demand for them on-road declines, is an important topic for continued policy discussion.

HEFA AJF offers significant air quality benefits compared to conventional jet fuel. As on-road diesel fleets shift to newer (post-2010) vehicles with modern pollution control, the air quality benefits of biomass-based diesel substitutes decline. This may create an opportunity to improve air quality by shifting feedstock from biomass-based diesel to AJF.

Alternative aviation fuels are increasingly a primary focus of transportation and fuel policy. The U.S., EU and other jurisdictions have adopted policies to increase the use of alternative aviation fuels. Most are setting volumetric or blend targets and screening by estimated life cycle GHG emissions and/or feedstock sources, and many are providing financial incentives.

Successfully reducing emissions from aviation will require one or more new technologies to emerge at commercial scale. Existing technologies and redirection of some on-road fuels can likely contribute to meeting the global demand for aviation fuel but do not have a plausible pathway to meet all aviation fuel demand. Electrochemical synthesis has emerged as a focus of EU aviation fuel policy, in part due to its potentially very-low-carbon profile. However, it would require efficiency improvements as well as massive deployment of renewable electricity generation—especially non-biomass sources—beyond that needed to decarbonize the electrical grid.

Key Areas of Uncertainty for Policymakers

For those developing a strategy to grow low-carbon AJF at scale, it is still unknown:

- How to best support continued growth of alternative aviation fuels without overinvesting in current technologies given a potential link to land use change and the uncertainty about which technology or technologies will dominate long-run alternative aviation fuel supply.
- How to develop guardrails that mitigate the risk of overgrowth in crop-based fuel production, with vegetable oils presenting a concern given current trends and policies in place.
- How, and when, to assign the limited amount of biomass feedstock to the sectors that appear difficult to electrify, e.g., aviation, marine, or outside transportation in chemical production or other bioindustry.
- How and when to build infrastructure, e.g., airport and fuel system upgrades, as needed to accommodate low carbon AJF given the complexities of airport operations and cost, space and safety concerns associated with airport changes.
- What the capacity is of battery electric or other ZEV aircraft to contribute to aviation, and how quickly they can commercialize.
- How much carbon budget is available for aviation, via offsets or CCS.
- To what extent operation improvements and more efficient aircraft can contribute to GHG reduction from aviation.
- To what extent CORSIA will drive real emission reductions as opposed to just offsetting them, and the scope for national governments to effectively take action to reduce emissions from international travel.

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