Decarbonizing Aviation: Challenges and Opportunities for Emerging Fuels

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List of Acronyms

In order of appearance:

CO_2 – carbon dioxide
SAFs – sustainable aviation fuels
GHG – greenhouse gas
SZEFs – scalable zero-emission fuels
ZCFs – zero-carbon fuels
DAC – direct air capture
U.S. – United States
RD&D – research, development, and deployment
EU – European Union
Mt – megatons
ICAO – International Civil Aviation Organization
IATA – International Air Transport Association
CORSIA – Carbon Offsetting and Reduction Scheme in International Aviation
A4A – Airlines for America
COP26 – the 26th UN Climate Change Conference
UK – United Kingdom
IACAC – International Aviation Climate Ambition Coalition
IRA – Inflation Reduction Act of 2022
LUC – land use change
NOX – nitrogen oxides
IEA – International Energy Agency
EIA – U.S. Energy Information Administration
DOE – U.S. Department of Energy
OPEC – Organization of the Petroleum Exporting Countries
SPS – Stated Policies Scenario, from IEA
H:C – hydrogen to carbon ratio
FCH – Fuel Cells and Hydrogen Joint Undertaking
BTC – biodiesel tax credit
RFS – Renewable Fuel Standard
EPA – U.S. Environmental Protection Agency
LCFS – Low Carbon Fuel Standard
DOT – U.S. Department of Transportation
USDA – U.S. Department of Agriculture
ASCENT – Aviation Sustainability Center
ZCFS – zero-carbon fuel standard
DOD – Department of Defense
FAA – Federal Aviation Administration
CLEEN – Continuous Lower Energy, Emissions, and Noise program
BETO – Bioenergy Technology Office
ETS – Emission Trading System
SES – Single European Sky
CSJU – Clean Sky Joint Undertaking
T&E – Transport & Energy
CfD – Contracts for Differences

Executive Summary

The aviation sector is a significant contributor to global warming.

It currently makes up two percent of carbon dioxide (CO_2) emissions, could potentially **triple by 2050** in the absence of meaningful policy changes. To reach net-zero emissions by 2050, this difficult-to-decarbonize sector will depend on smart investments and effective policies to deploy and rapidly scale up new technologies over the coming decades.

Sustainable Aviation Fuels (SAFs) are the most frequently touted solution for reducing the **aviation** sector's greenhouse gas (GHG) emissions, as a replacement to traditional kerosene jet fuels. Despite efforts to impose some definitional consistency, the term SAF is neither well defined nor consistently deployed. In addition to fuels made from waste matter and other environmentally sustainable feedstocks, the term is sometimes applied to fuels made from biogenic feedstocks that are carbon intensive (on a lifecycle basis) or to fuels made from non-biogenic feedstocks that have high energy, land, and water requirements. Effectively, the term SAFs suggests that biofuels that could be low-carbon are necessarily sustainable — which is not always the case. Further, the term SAF typically excludes other nascent energy carriers like hydrogen and battery electric propulsion. Because the vast majority of fuels referred to as SAFs are derived from biomass, **this paper focuses on aviation biofuels.** It examines the environmental merits of aviation biofuels, assesses the implications of replacing conventional jet fuel exclusively with biofuel, and offers an alternative framing for aviation sector decarbonization that puts the emphasis on the carbon intensity of aviation fuel options.

In particular, **this paper also examines the potential role for scalable zero-emission fuels (SZEFs) in decarbonizing the aviation sector.** The Global Maritime Forum defines SZEFs[1] to include zero-carbon fuels (ZCFs) — which are fuels like hydrogen that do not contain any carbon and thus can be consumed without emitting carbon dioxide — as well as low-net-emission fuels such

[1] Søgaard, K., et al. (2022). *Insight Brief: How the EU can catalyze the global transition to zero-emission shipping and the green hydrogen economy*. Global Maritime Forum. https://www.globalmaritimeforum.org/news/insight-brief-how-the-eu-can-catalyze-the-global-transition-to-zero-emission-shipping-and-the-green-hydrogen-economy.

as synthetic kerosene. To be considered a SZEF, fuels that contain carbon (such as synthetic kerosene) need to achieve net-zero or near net-zero emissions by utilizing carbon captured from the air through direct air capture (DAC) or a similar process so that there is no (or very low) net increase to the carbon emissions in the atmosphere. Electrification will also be explored as a niche decarbonization strategy for some parts of the aviation sector, though electricity is not typically considered a SZEF or ZCF.

To displace conventional jet fuel in the coming decades, a combination of aviation biofuels, SZEFs, and low-carbon electricity will need to be used to meet global aviation energy demand amounting to about 16 quadrillion British thermal units (quads[2]) per year in 2030 and about 19 quads per year in 2040. If aviation biofuels (the only widely available alternative to conventional jet fuel today) were exclusively used to meet this demand, it would require quadrupling current global biofuel production by 2030, and almost quintupling it by 2040. While the United States (U.S.) is already the global leader in biofuel production, biofuel production would need to ***more than double*** over the coming decades to meet domestic aviation energy demand.

Ramping up aviation biofuel production in this way is a worrisome prospect given that bioenergy already faces several sustainability and supply chain challenges. Harvesting, processing, transporting, and storing the required quantity of biomass feedstock cost-effectively would introduce new supply chain challenges that have yet to be addressed in real world scenarios. It could also have detrimental land use and water use implications, contribute to the displacement of existing agriculture, harm biodiversity, exacerbate food insecurity, and disrupt existing natural carbon sequestration processes.

The limits of scaling up present-day biomass-derived SAFs and the need to aggressively decarbonize the aviation sector demands that we shift away from the conventional criteria for SAFs and pursue a wider range of energy options that meet stringent low-carbon intensity standards. These options are likely to include aviation biofuels, SZEFs (including both zero-carbon fuels and low-net-emission synthetic fuels, as described above), and electric propulsion. Public- and private-sector stakeholders also need to develop lifecycle analysis protocols that consider full lifecycle GHG emissions from aviation fuels. In addition, while carbon offsets may contribute to aviation sector decarbonization, an overreliance on offsets jeopardizes the aviation sector's ability to decarbonize, if, for example, it is later discovered that the offsets do not provide substantial permanent CO_2 storage and alternative options are not available because of lack of attention or investment

Aviation biofuels have been used synonymously to refer to SAFs largely due to their early prominence in the aviation sector as an alternative to conventional jet fuel. This paper focuses much of its analysis on aviation biofuels, particularly given the unique characteristics associated with their production, and it proposes a shift away from the conventional and overly loose framing of SAFs towards low- and zero-carbon alternatives like *demonstrably low-carbon* aviation biofuels, SZEFs, and electric propulsion.

Decarbonizing the aviation sector will require bold technology investments and a policy and regulatory response that is significantly more comprehensive than we have seen to date. A coherent response would include public investments in research, development, and deployment (RD&D) to stimulate innovation in next generation fuels, tax credits or subsidies to incentivize investment and production, regulations to accelerate demand, and technical standards — including full lifecycle (well-to-wake) accounting of the GHG emissions tied to the production, transport, and use of aviation fuels — to ensure aviation biofuels, SZEFs, and electric propulsion are meeting low- or zero-carbon emissions standards.

This paper:

- **Analyzes** the aviation energy demand that will need to be replaced in order to decarbonize the aviation sector (Part 2)
- **Assesses** the implications of using aviation biofuels to meet this demand (Part 3)
- **Explores** a number of alternatives to aviation biofuels that have potential to be promising (Part 4)
- **Recommends** policies for the U.S. and EU to drive innovation in and adoption of low-carbon aviation biofuels, SZEFs, and electric propulsion to decarbonize the aviation sector (Part 5)

[2] A quad is a unit of energy equivalent to 10^{15} BTU (or a "quadrillion" BTU). For context, total primary energy consumption in the United States in 2020 was 93 quads, according to the U.S. Energy Information Administration. 16 quads equal 16.88 Exajoules.

SECTION 1

The Case for Decarbonizing Aviation

The aviation sector's climate impact

GHG emissions from the aviation sector have increased rapidly in recent decades, making up 920 Megatons (Mt) of the global CO_2 emissions from fossil fuels in 2019 compared to only 706 Mt in 2013 — a 30% increase.[3] This is largely explained by the increase in commercial passenger flight activity, which, prior to the COVID-19 pandemic, was growing over 6% per year over the last decade.[4] Passenger transport accounted for 85% of these emissions, with the remaining aviation emissions attributed to cargo and dedicated freight.[5] More than half of these emissions come from the U.S. (23%), the EU (19%), and China (13%).[6]

In the face of this rapid growth, the energy intensity of air travel has decreased 2.8% per year.[7] Despite reductions in energy intensity, recent studies estimated aviation emissions were on track before the COVID-19 pandemic to triple by 2050, potentially accounting for 25% of global CO_2 emissions across all sectors.[8] The COVID-19 pandemic has had a substantial negative impact on the aviation industry, with the International Civil Aviation Organization (ICAO) estimating a 60%

3 Graver, B., Rutherford, D., & Zheng, S. (2020, October). *CO2 emissions from commercial aviation: 2013, 2018, and 2019*. International Council on Clean Transportation. https://theicct.org/sites/default/files/publications/CO2-commercial-aviation-oct2020.pdf

4 Monschauer, Y., et al. (2021, November). *Aviation*. International Energy Agency. https://www.iea.org/reports/aviation

5 Graver, B., Rutherford, D., & Zheng, S. (2020, October). *CO2 emissions from commercial aviation: 2013, 2018, and 2019*. International Council on Clean Transportation. https://theicct.org/sites/default/files/publications/CO2-commercial-aviation-oct2020.pdf

6 Graver, B., Rutherford, D., & Zheng, S. (2020, October). *CO2 emissions from commercial aviation: 2013, 2018, and 2019*. International Council on Clean Transportation. https://theicct.org/sites/default/files/publications/CO2-commercial-aviation-oct2020.pdf

7 Monschauer, Y., et al. (2021, November). *Aviation*. International Energy Agency. https://www.iea.org/reports/aviation

8 Graver, B., Rutherford, D., & Zheng, S. (2020, October). *CO2 emissions from commercial aviation: 2013, 2018, and 2019*. International Council on Clean Transportation. https://theicct.org/sites/default/files/publications/CO2-commercial-aviation-oct2020.pdf

decline in passengers and 50% reduction in seats offered by airlines.[9] Due to a significant drop in passenger demand for air travel, the International Air Transport Association (IATA) has estimated that CO_2 emissions from aviation dropped 47% in 2020 (488 Mt) and will remain 33% below pre-COVID-19 levels in 2021 (619 Mt).[10] Passenger demand is still expected to fully recover, though slowly — an analysis by McKinsey anticipates that passenger traffic will not return to 2019 levels before 2024.[11]

Current efforts to decarbonize

As part of the global effort to limit catastrophic impacts of climate change, the aviation sector needs to fully decarbonize by 2050. Both roadblocks and opportunities for achieving this have emerged as airlines devise strategies to adapt to the disruption caused by COVID-19. Today, kerosene, a carbon-intensive hydrocarbon fuel derived from petroleum, makes up more than 99.5% of aviation fuel.[12] Kerosene has several properties that have made it globally ubiquitous as an aviation fuel. It has relatively high energy density,[13] has a low freezing point and low viscosity so it does not clog up aircraft engines, and is cheaper than gasoline.[14] Aircraft engines, global storage and supply chain infrastructure, and safety regulations have all been designed around the widespread use of kerosene as a jet fuel, making any transition away from the fuel more difficult. Total demand for kerosene is expected to continue to grow through 2030, further complicating efforts to fully decarbonize the sector. Given this status quo, the aviation sector has a long way to go to achieve decarbonization, and recent commitments to reduce air travel's impact on climate are insufficient to achieve decarbonization in the necessary timeframe.

ICAO, an aviation technical body of the United Nations that serves as a global policy and standards forum, adopted a resolution for the aviation sector to achieve 2% annual fuel efficiency improvements through 2050 and carbon neutral growth from 2020 onwards, effectively maintaining existing aviation emissions through mid-century.[15] ICAO's plan seeks to achieve carbon neutral growth through the use of SAFs and a mechanism known as the Carbon Offsetting and Reduction Scheme in International Aviation (CORSIA) to offset any growth in aviation emissions (see Part 4).

These targets are encouraging but insufficient. Airlines have improved fuel efficiency by an average of 2% per year since 2009, which shows that they are capable of meeting or surpassing existing targets and points to the need for even more ambitious targets in the years ahead.[16] In recent months, many airlines have responded to that need by committing to more ambitious decarbonization targets. The oneworld group of 14 member airlines has committed to net-zero carbon emissions by 2050,[17] and members of the industry trade organization Airlines for America (A4A), including American Airlines, Delta, JetBlue, Southwest, and United Airlines, have also committed to achieve net-zero by 2050.[18] The IATA, a global trade association representing 290 airlines, adopted a target of eliminating

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9 International Civil Aviation Organization. (2022, May 8). *Effects of novel coronavirus (COVID-19) on civil aviation: Economic impact analysis.* https://www.icao.int/sustainability/Documents/COVID-19/ICAO_Coronavirus_Econ_Impact.pdf

10 International Air Transport Association. (2020). *Economic performance of the airline industry: 2020 end-year report*. https://www.iata.org/en/publications/economics/?page=8&Search=&Ordering=DateDesc

11 Bouwer, J., Saxon, S., & Wittkamp, N. (2021, April 2). *Back to the future? Airline sector poised for change post-COVID-19*. McKinsey & Company. https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/back-to-the-future-airline-sector-poised-for-change-post-covid-19

12 International Energy Agency. (2021). *Aviation*. https://www.iea.org/fuels-and-technologies/aviation

13 Petit, B. (2003). Ramjets and scramjets. *Encyclopedia of Physical Science and Technology*, 867-884. https://doi.org/10.1016/B0-12-227410-5/00909-1

14 Monroe Aerospace. (2019, April 29). *Why airplanes use kerosene rather than plain gasoline for fuel*. https://monroeaerospace.com/blog/why-airplanes-use-kerosene-rather-than-plain-gasoline-for-fuel/

15 International Civil Aviation Organization. (2019). *Climate change*. https://www.icao.int/environmental-protection/pages/climate-change.aspx

16 Air Transport Action Group. (2019, January). *Tracking aviation efficiency*. https://aviationbenefits.org/media/167219/fact-sheet_3_tracking-aviation-efficiency_3.pdf

17 Oneworld. (2021, August 31). *Oneworld member airlines commit to net zero carbon emissions by 2050*. https://www.oneworld.com/news/2021-08-31-oneworld-outlines-path-to-net-zero-emissions-by-2050

18 Nastu, J. (2021, April 5). US airlines commit to achieve net-zero, help industry reach 2 billion gallons of sustainable aviation fuel by 2030. *Environmental Leader*. https://www.environmentalleader.com/2021/04/us-airlines-commit-to-achieve-net-zero-help-industry-reach-2-billion-gallons-of-sustainable-aviation-fuel-by-2030/

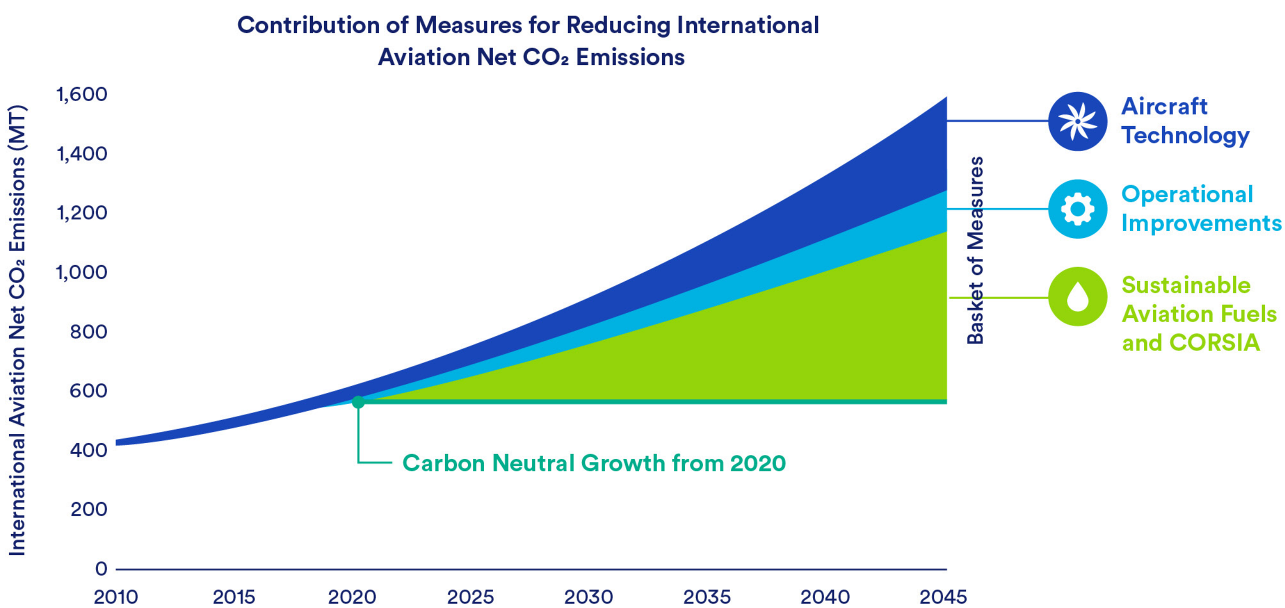
CO_2 emissions on a net basis, although individual airlines can set their own targets.[19] At the 26th UN Climate Change Conference (COP26), 20 countries, including the U.S., the United Kingdom (UK), and Japan, launched the International Aviation Climate Ambition Coalition (IACAC) to reduce aviation emissions consistent with the broader goal of limiting warming to 1.5 degrees Celsius.[20] This coalition will need to apply pressure to ICAO and other bodies to establish global, industry-wide net-zero plans while lacking representation from large aviation markets like China and India. While the pathway to achieving net-zero emissions by 2050 is opaque, airlines and aviation industry associations have set more ambitious targets than ICAO, the global aviation sector's technical body.

The role of sustainable aviation fuels

While operational and fleet efficiencies as well as changing consumer behaviors may be able to reduce the carbon intensity of air travel in the near term, more needs to be done to fully decarbonize the aviation sector. In part because alternatives like fleet electrification and hydrogen fuel adoption are not ready for use yet at commercial scales, SAFs have emerged as the main pathway for reducing the aviation sector's climate impact. Many of the airline pledges mentioned above rely heavily on the production and deployment of SAFs, and A4A has announced it plans to make 2 billion gallons of SAFs available to U.S. airlines in 2030 to help achieve this target.[21]

Figure 1: ICAO's Plan Maintains CO_2 Emissions from International Aviation at their Current Levels

Source: ICAO



19 Philip, S. V., Schlangenstein, M., & Jasper, C. (2021, October 4). Airline industry targets net-zero carbon emissions by 2050. *Bloomberg*. https://www.bloomberg.com/news/articles/2021-10-04/airline-industry-targets-net-zero-carbon-emissions-by-2050

20 Adler, K. (2021, November 10). COP26: Nations come together to promote aviation decarbonization. *IHS Markit*. https://cleanenergynews.ihsmarkit.com/research-analysis/cop26-nations-come-together-to-promote-aviation-decarbonization.html

21 Nastu, J. (2021, April 5). US airlines commit to achieve net-zero, help industry reach 2 billion gallons of sustainable aviation fuel by 2030. *Environmental Leader*. https://www.environmentalleader.com/2021/04/us-airlines-commit-to-achieve-net-zero-help-industry-reach-2-billion-gallons-of-sustainable-aviation-fuel-by-2030/

IATA defines SAFs as sustainable non-fossil-derived fuel with "chemical and physical characteristics that are almost identical to conventional jet fuel… can be safely mixed with jet fuel to varying degrees, use the same supply infrastructure, and do not require the adaptation of aircraft or engines."[22] The difficulty with this definition is that it is broad enough to include biofuels made from a variety of biological feedstocks and fuels made from non-biological sources, each with varying carbon intensity levels, energy requirements, land and water needs, and hydrogen inputs — but IATA offers limited guidance with respect to key questions around how those impacts should be assessed. A similar set of problems cloud the definition of "sustainable aviation fuel" set forth in the Inflation Reduction Act of 2022 (IRA), a U.S. climate law that makes tax credits available to companies that blend SAF into the aviation fuel mix.[23] Lifecycle modeling indicates that the net climate impact of some biofuels is better than that of conventional kerosene jet fuel, but biofuels may perform worse when assessed against other environmental or social metrics. Moreover, the IATA and IRA definitions lack the type of guardrails needed to exclude the use of fuels derived from *unsustainable* feedstocks. These challenges are especially acute for biofuels, which make up the vast majority of non-conventional jet fuel in use today.[24]

Problems with the term "sustainable aviation fuels"

- **"SAF" is obfuscating:** The vast bulk of fuels referred to as SAFs are in fact biofuels, a fuel type with a checkered history.
- **"SAF" is imprecise:** "Sustainable" is often used interchangeably with "climate friendly," but the terms are not synonymous. A process that harvests plant matter and converts it to fuel is typically considered to be sustainable as long as plant matter is eventually fully regrown on the harvested plot of land. The regrowth time matters from a climate perspective, though, because small immature plants absorb less carbon dioxide than large mature plants. Consequently, using slow-growing biomass to make biofuels might be considered "sustainable" even if the process causes an increase in atmospheric CO_2 levels for years or decades during the regrowth period.
- **"SAF" is misleading:** The term SAF is sometimes applied to biofuels that offer little or no ecological, social, or climate benefits.

Despite the questions around the sustainability and climate benefits of SAFs, IATA estimated that 100 million liters of SAFs would be produced in 2021, with 14 billion liters of SAFs in forward purchase agreements.[25]

SAFs derived from biofuels (referred to as aviation biofuels) have several benefits as well as drawbacks, some of which will be explored in more depth in this paper. The primary appeal of aviation biofuels is their potential to reduce net CO_2 emissions compared to conventional jet fuels. Their largest drawbacks, however, are the uncertainties around their scalability and the potential for associated sustainability problems — including high levels of land use change (LUC) — that can in turn drive up their net CO_2 emissions. (Another drawback they share with other alternative aviation fuels is that they are expensive relative to conventional jet fuel; unlike other alternatives, however, the production of truly sustainable biofuels is likely to get *more* expensive on a per unit basis as production scales up, due to the limited supply of appropriate feedstocks).

The production of aviation biofuels also requires substantial volumes of hydrogen to support a process called hydrotreating, in which heat and pressure are used to react hydrogen with fats and oils derived from biomass. The hydrogen currently used to make aviation biofuels is not sustainably produced and thus has GHG emissions associated with its production. Minimizing the lifecycle GHG emissions of aviation biofuels will require that the hydrogen used in that process is produced from low- and zero-emission production pathways.

[22] International Air Transport Association. (n.d.-b). *Fact sheet: What is SAF?* International Air Transport Association. https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-what-is-saf.pdf

[23] Pub. Law. No. 117-169 (amending 26 U.S.C. sec 40), 116, https://www.congress.gov/117/bills/hr5376/BILLS-117hr5376enr.pdf

[24] DNV. (2020). *Energy transition outlook 2021 launch*. https://eto.dnv.com/2020

[25] International Air Transport Association. (n.d.-a). *Developing sustainable aviation fuel (SAF)*. Retrieved April 19, 2022, from https://www.iata.org/en/programs/environment/sustainable-aviation-fuels/#tab-2

The table below details key benefits and risks for aviation biofuels.

Table 1: Benefits and Risks for Aviation Biofuels

Benefits of Aviation Biofuels	Risks of Aviation Biofuels
Potentially *low* lifecycle CO_2 emissions (e.g., 80% lower than conventional fuels in some cases[26]) if, for example, waste biomass is used to make the biofuel	Potentially *high* lifecycle CO_2 emissions if, for example, a significant amount of land is required to grow the biomass used to make the biofuel
Contains fewer impurities like sulfur relative to petroleum fuels	Limits on the availability of biomass and arable land could create competition with other agricultural sectors, and the reallocation of farmland and other agricultural inputs to biofuel production could exacerbate food insecurity
Production is not limited to locations where fossil fuels can be extracted, potentially enabling a more diverse geographic supply and a degree of energy security	Does not eliminate aircraft condensation trails, which include pollutants like nitrogen oxides (NOX)[27]
Decreases exposure to fluctuating prices of crude oil, enabling more certainty in planning and budgeting for long-term operating expenses	Significant infrastructure required to scale-up biofuel production, and not yet cost-competitive with fossil fuels (production cost of aviation biofuels was approximately four times higher than the market price of kerosene jet fuel in 2020[28])

26 Verdon, M. (2021, April 21). This new bio-fuel uses old cooking oil to fly jets with 80% less carbon emissions. *Robb Report*. https://robbreport.com/motors/aviation/bio-fuel-jets-80-percent-less-carbon-emissions-1234608908/

27 Caiazzo, F. et al. (2017). Impact of biofuels on contrail warming. *Environmental Research Letters*, 12(11), 114013. https://doi.org/10.1088/1748-9326/AA893B

28 International Energy Agency. (2020, November 12). *Fossil jet kerosene market price compared with HEFA aviation biofuel production cost, 2019-2020.* https://www.iea.org/data-and-statistics/charts/fossil-jet-kerosene-market-price-compared-with-hefa-aviation-biofuel-production-cost-2019-2020

SECTION 2

Projected Demand for Low- and Zero-Carbon Energy Options for Aviation

GHG emissions from air travel make up 2% of global emissions and are projected to significantly increase over the coming decades[29] driven primarily by increased demand in emerging economies like China and India.[30] While the long-term impact of COVID-19 on the aviation sector is difficult to predict at this stage, the fact remains that decarbonization of the sector will be particularly challenging in the years ahead. This is primarily due to the high dependence on kerosene jet fuel as the primary energy driver for air travel, with few sustainable alternatives currently used at scale.

This section evaluates the aviation fuel demand projections from various organizations, agencies, and companies to determine the scale of aviation biofuels, SZEFs, and electricity needed to replace all projected demand for conventional jet fuel. We assume here, for the sake of argument, that biofuels and the other energy options contemplated for aviation sector decarbonization are indeed carbon neutral, and therefore that full adoption of these fuels would fully negate all aviation fuel emissions. This is a substantial assumption, particularly for biofuels — a point we will return to later.

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29 Overton, J. (2019, October 17). *Fact sheet | the growth in greenhouse gas emissions from commercial aviation (2019)*. Environmental and Energy Study Institute. https://www.eesi.org/papers/view/fact-sheet-the-growth-in-greenhouse-gas-emissions-from-commercial-aviation

30 Press Trust of India. (2019, June 2). India, China to account for nearly half of air passenger growth in two decades, says IATA. *The Economic Times*. https://economictimes.indiatimes.com/industry/transportation/airlines-/-aviation/india-china-to-account-for-nearly-half-of-air-passenger-growth-in-two-decades-says-iata/articleshow/69618996.cms

Demand for air travel

Leading up to the global shock to the aviation sector created by the COVID-19 pandemic, demand for air travel had grown steadily for decades. Between the end of the 2008 to 2009 recession and 2019, the number of air travel passengers carried per year had nearly doubled from 2.25 billion to 4.39 billion.[31] IATA estimates that international passenger demand in 2020 was 75.6% below 2019 levels and domestic demand was down 48.8% compared to 2019.[32] The International Energy Agency (IEA) estimates there will be a sustained reduction in aviation fuel demand due to behavior changes following COVID-19, with changes to business travel policy and the shift to video conferencing decreasing business passenger activity by 10% compared to its pre-COVID-19 trajectory.[33] McKinsey estimates that the recovery in leisure travel will outpace the recovery in business travel, and business travel may only recover to 80% of pre-pandemic levels by 2024.[34] Nonetheless, overall demand for air travel is expected to pick up, particularly in emerging economies as travel demand increases with economic growth.

Data sources

This section compares the global aviation fuel demand projections made by organizations, agencies, and companies to determine a projected range of expected aviation fuel demand in 2030, 2040, and 2050. After conducting a search for publicly available energy projections that provided global aviation fuel consumption projections spanning multiple decades, the following four data sources were selected:

- **DNV** is a consultancy that serves as a technical advisor to the oil and gas and maritime shipping industry. Projections were sourced from DNV's Energy Transition Outlook 2020 report and dataset.
- **The U.S. Energy Information Administration (EIA)** is a statistical and analytical agency within the U.S. Department of Energy (DOE). Projections were derived from the EIA's Annual Energy Outlook for U.S.-based energy projections and the International Energy Outlook for global projections.
- **The International Energy Agency (IEA)** is an intergovernmental organization under the OECD that produces global energy analysis, data, and policy recommendations. Energy projections were sourced from IEA's World Energy Outlook 2020 report and dataset.
- **Organization of the Petroleum Exporting Countries (OPEC)** is an intergovernmental organization of 13 oil-exporting countries. Energy Projections were sourced from OPEC's World Oil Outlook 2020 report and dataset.

Projected aviation energy demand

Aviation fuel energy demand is expected to rise over the next three decades, driven by growing passenger demand that appears to be outpacing improvements in energy efficiency.[35] Domestic aviation fuel consumption in the U.S. stood at 1.86 quads in 2020 (down from 2.64 quads in 2019) and is projected to increase to 3.2 quads in 2030, 3.6 quads in 2040, and 4.1 quads in 2050 per EIA.[36] Estimates for global aviation energy demand range from 15.3 to 17.1 quads in 2030, 17.2 to 20.6 quads in 2040, and 19 to 23.5 quads in 2050 (see Figure 2 on the next page).

31 The World Bank. (n.d.). *Air transport, passengers carried*. Retrieved April 20, 2022, from https://data.worldbank.org/indicator/IS.AIR.PSGR

32 International Air Transport Association. (2021, February 3). *2020 worst year in history for air travel demand*. https://www.iata.org/en/pressroom/pr/2021-02-03-02/

33 International Energy Agency. (2020a). *World energy outlook 2020* (p. 184). https://www.iea.org/reports/world-energy-outlook-2020

34 Bouwer, J., Saxon, S., & Wittkamp, N. (2021, April 2). *Back to the future? Airline sector poised for change post-COVID-19*. McKinsey & Company. https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/back-to-the-future-airline-sector-poised-for-change-post-covid-19

35 Overton, J. (2019, October 17). *Fact sheet | the growth in greenhouse gas emissions from commercial aviation (2019)*. Environmental and Energy Study Institute. https://www.eesi.org/papers/view/fact-sheet-the-growth-in-greenhouse-gas-emissions-from-commercial-aviation

36 Energy Information Administration. (2021, October 6). *International energy outlook 2021*. https://www.eia.gov/outlooks/ieo/

Figure 2: Global Aviation Energy Demand

Source: DNV, EIA, OPEC, IEA

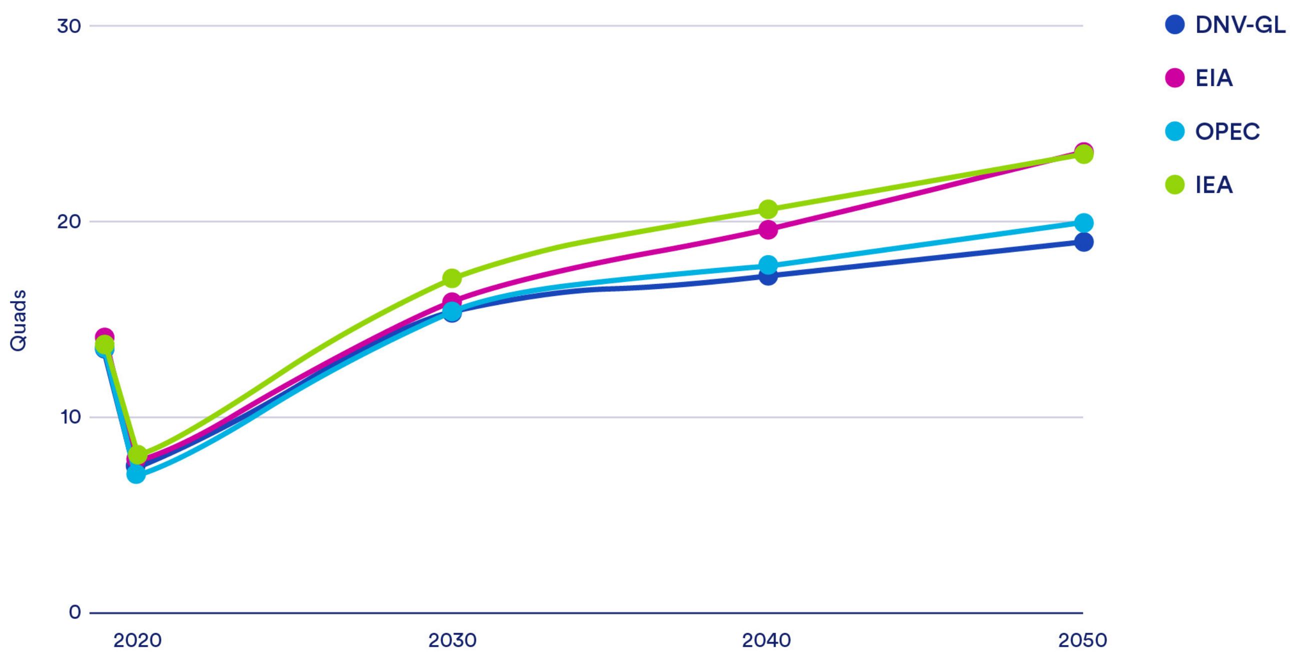


Table 2: Projected Global Aviation Energy Demand by Data Source

Source (figures normalized to quads)	2019	2020	2030	2040	2050
● **DNV** Energy Transition Outlook 2021	13.5	7.5	15.3	17.2	19
● **EIA** International Energy Outlook 2021	14.1	7.9	15.9	19.6	23.5
● **OPEC** World Oil Outlook 2021	13.6	7.09	15.4	17.8	19.9
● **IEA** World Energy Outlook 2021	13.7	8.1	17.1	20.6	23.4
Calculated average for projected years	*N/A*	*N/A*	*15.9*	*18.8*	*21.5*

The substantial differences in the range of estimates are driven by varying assumptions about passenger demand as well as fleet efficiency. Some assumptions critical to highlight include:

- DNV's projection assumes significant gains in aircraft's energy efficiency. Despite an estimated doubling of annual air trips by 2050, they predict fuel use in aviation will only increase 9% primarily due to these efficiency gains.
- IEA's Stated Policies Scenario (SPS) assumes that the 10% decline in business passenger activity due to COVID-19 will be sustained, reducing oil demand in 2030 by 0.2 million barrels per day, but expects oil demand will increase leading up to 2030 driven primarily by increased aviation demand in Asia and emerging markets (nearly doubling by 2030).[37]
- EIA's Reference Case assumes increased economic activity will help return travel to 2019 levels by 2030.
- OPEC's World Oil Outlook is projecting a period of oil demand "catching up" in sectors affected by COVID-19, particularly the aviation sector, expecting air travel demand to reach 2019 levels in 2023 to 2024. OPEC's dataset projects out to 2045. The 2050 figure was extrapolated by applying the oil demand growth rate from 2040-2045 to the 2045-2050 timeframe.

Given these differences, this analysis uses the average across projections to arrive at estimated global aviation energy demand of 15.9 quads per year for 2030, 18.8 quads per year for 2040, and 21.5 quads for 2050. These figures represent the aviation sector's energy demand. That demand is currently met almost entirely by conventional jet fuel. To eliminate aviation sector emissions, that jet fuel will need to be replaced by low-carbon aviation biofuels, SZEFs, and zero-carbon electricity.

Table 3: Estimated Future Aviation Sector Energy Demand

Estimated Aviation Energy Demand (quads)	2030	2040	2050
Global	15.9	18.8	21.5
Domestic U.S.	3.2	3.6	4.1

[37] International Energy Agency. (2020a). *World energy outlook 2020* (p. 184). https://www.iea.org/reports/world-energy-outlook-2020

SECTION 3

The Challenges of Meeting Aviation Energy Demand with Only Biofuels

Today, biofuels account for the vast bulk of what is described as SAFs, even though many biofuels are sourced from biomass feedstocks that cannot be sustainably scaled up and are associated with a wide range of land, water, and energy requirements.[38] Replacing conventional jet fuel with aviation biofuels would require an unprecedented ramp-up of biofuel production in the coming years. Not only would the scale-up of biofuel production require substantial conversion of biomass feedstocks, it would also require massive repurposing of biofuel production from other uses toward aviation. While theoretical models demonstrate this demand could be met with existing biomass feedstocks, real world production of biofuels at this scale will introduce a series of new supply challenges, including the availability of biomass feedstocks, land-use limitations, new processing inputs, and supply chain constraints.

The biofuels industry has so far proven itself capable of making huge volumes of biofuel (i.e., billions of gallons annually) only when it uses huge tracts of land, often to the detriment of the environment. The aviation industry is appropriately focused on biofuels made from waste, but it has not yet been demonstrated that waste-based production pathways are viable at massive, commercially relevant scales and that there are sufficient volumes of waste to meet demand from the aviation sectors and from other bioenergy-consuming sectors. Until then, it should not be assumed that using biofuels to meet a substantial portion of aviation sector energy demand will not pose LUC-related risks.

[38] Jonathan Lewis, EPA's Report on the Environmental Impacts of the RFS (July 9, 2018) (https://www.catf.us/2018/07/epa-report-environmental-impacts-biofuels/#038;swpmtxnonce=1eeee8822a).

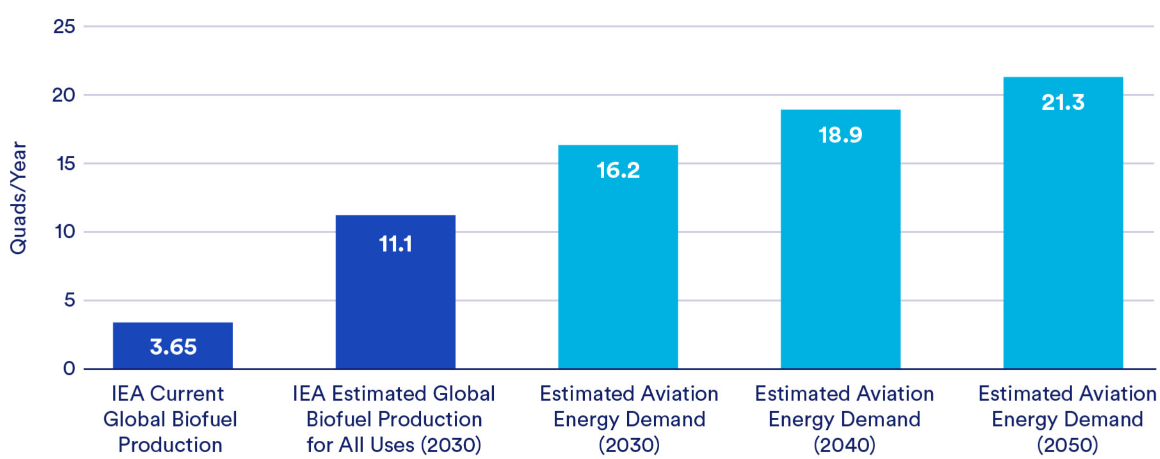
The supply of biomass feedstocks that can support the production of low-emissions biofuels is limited — so limited, in fact, that projected energy demand for aviation will exceed the projected availability of such biofuels. In addition, because the climate impact of biofuel production and use depends on physical, biological, and chemical changes to vast landscapes that are difficult or impossible to measure at commercial scale, there is significant uncertainty about the lifecycle carbon intensity of most types of biofuel.[39] Finally, although more ambitious goals are sometimes mentioned, the aviation sector is targeting biofuels that only achieve a 50% reduction in lifecycle GHG emissions compared to conventional jet fuel — as evidenced in the U.S. government's Sustainable Aviation Fuel Grand Challenge.[40]

Global production

According to the IEA, current global biofuel production across all sectors stands at 3.65 quads per year.[41] As noted above, biofuels and SAFs are not synonymous; this IEA report does not look specifically at SAFs and instead covers biofuels across all sectors.

The average estimates of global demand for aviation biofuel determined in the previous section are 15.9 quads by 2030, 18.8 quads by 2040, and 21.5 quads by 2050. Therefore, meeting this demand would require more than quadrupling global biofuel production by 2030 and almost quintupling global biofuel production by 2040 — a worrisome prospect, given that bioenergy production is already bumping up against sustainability thresholds — and it would require reserving all that biofuel for aviation. This would represent a production scale that outpaces IEA's own 2030 estimates for biofuel production under their Sustainable Development Scenario, one of its more aggressive energy transition scenarios. IEA estimates that biofuel production across all sectors in 2030 will reach 11.1 quads per year. However they assume that aviation biofuel demand will only be 1.2 quads by 2030 (approximately 10% of total biofuel production).
To fully meet the aviation sector's projected energy demand with only biofuels, biofuel production would need to scale to 15.9 quads by 2030, 18.8 quads by 2040, and 21.5 quads by 2050 *in addition* to all other biofuel use cases, vastly outstripping IEA's 11.1 quads per year of biofuel production projected in 2030.

Figure 3: Global Biofuel Production vs. Global Aviation Energy Demand



39 Plevin, R. J., et al. (2015). Carbon Accounting and Economic Model Uncertainty of Emissions from Biofuels-Induced Land Use Change, Environmental Science & Technology. https://doi.org/10.1021/es505481d.

40 U.S. Department of Energy. (n.d.). *Sustainable aviation fuel grand challenge*. Retrieved April 24, 2022, from https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge

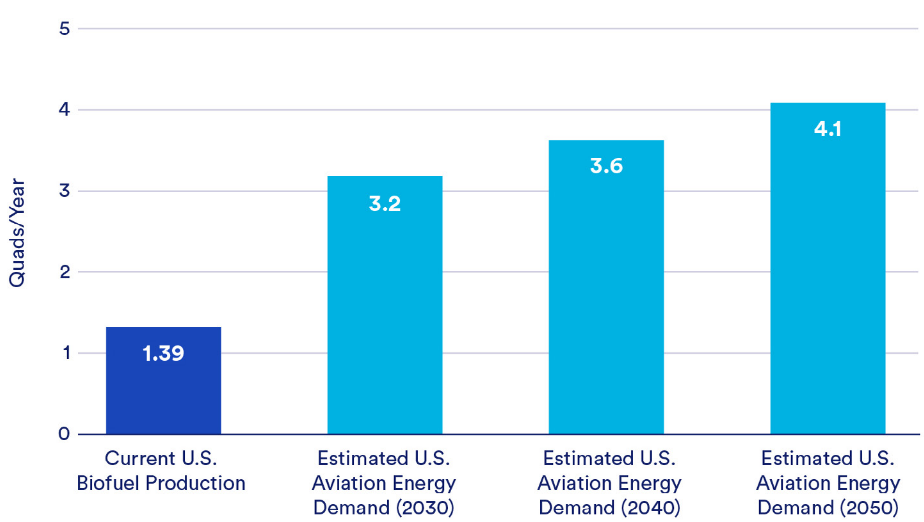
41 Moorhouse, J. (2021, November). *Transport biofuels*. International Energy Agency. https://www.iea.org/reports/transport-biofuels

U.S. biofuels production

Today, the U.S. produces 10 million gallons (approximately 45.5 million liters) per year of fuel that is marketed as "SAF" — a volume that amounts to only about 0.04% of the 26 billion gallons of fuel consumed by the country's aviation sector.[42] Total annual U.S. biofuel production across all sectors in 2019 stood at 1.39 quads.[43] According to EIA's Annual Energy Outlook 2021, estimated U.S. commercial aviation fuel consumption in 2030, 2040, and 2050 are 3.2, 3.6, and 4.1 quads respectively. U.S. biofuel production, assuming it is entirely repurposed for aviation, would need to more than double over the coming decades to meet domestic demand from an already relatively high baseline. The U.S. leads the world in biofuel production and has committed tens of millions of acres to feedstock cultivation. While this degree of scale-up is less extreme than the global production scenario, it would play out in an agricultural market that already accommodates feedstock cultivation at a massive scale to support the production of biofuels targeted at other use cases, like ethanol and biodiesel for cars and trucks. Actual domestic biofuel production would need to increase well beyond current production levels to meet demand from those other sectors as well as the substantial U.S. aviation fuel needs by 2030 and 2040. Given the considerable challenges and limited alternative options for decarbonizing aviation compared to other sectors, low-carbon and carbon-neutral biofuels would ideally be prioritized for use by the aviation sector over other biofuel-consuming sectors — either by the market (assuming it rewards GHG reductions) or by targeted regulation.

Global and domestic biofuel production have both grown significantly in recent years, yet biofuels have displaced less than 1% of conventional jet fuel to date.[44] Current and projected levels of biofuel production are nowhere near sufficient to meet aviation fuel demand in addition to biofuel's many other use cases. This degree of scale-up on its own may be unrealistic and will only be further complicated by a series of practical challenges, including the availability of biomass, land-use limitations, and supply chain constraints, each of which are explored further below.

Figure 4: U.S. Biofuel Production vs. U.S. Aviation Energy Demand



42 National Business Aviation Association. (2021, May 5). *DOE: U.S. Has the resources to replace all jet-a with saf.* https://nbaa.org/aircraft-operations/environmental-sustainability/doe-u-s-has-the-resources-to-replace-all-jet-a-with-saf/

43 Moorhouse, J. (2021, November). *Transport biofuels*. International Energy Agency. https://www.iea.org/reports/transport-biofuels

44 DNV. (2020). *Energy transition outlook 2021 launch*. https://eto.dnv.com/2020

Biomass availability

The first major supply constraint in meeting demand for aviation with SAFs that are primarily biofuels is biomass availability. The box below briefly describes the feedstocks that can be used for biofuels, which impact availability.

Two notable reports in recent years have modeled potential U.S. availability of biomass. Since international data on biomass availability is both limited and unreliable, the following section focuses on the U.S. as both a major consumer and producer of biofuel.

First, Princeton's Net Zero America study envisions biomass playing an important role in the production of electricity, hydrogen, and biofuels for the U.S. to achieve net-zero emissions by 2050.[45] It establishes two biomass supply scenarios, a lower bound (delimited biomass potential) and a higher bound (high biomass potential). The lower bound scenario includes agricultural and woody residues as well as wastes and some perennial energy grasses, whereas the higher bound scenario includes additional energy crop biomass that requires some conversion of pasture and cropland.[46] The higher bound scenario is largely based on DOE's 2016 Billion Ton Study of the projected supply of biomass feedstocks available for energy uses in the U.S. through 2040.[47]

Total biomass availability eepends on the biomass feedstocks used: An overview of biomass feedstocks

Biomass feedstocks are plant, algal, and other biogenic resources that can be converted to a fuel or other energy products and can take several different forms. The vast majority of biofuels produced to date have been made from farm-grown row crops like corn, soy, oil palm, and rapeseed (canola). The large commitments of land, water, and other inputs required to grow these biomass feedstocks often undermine the climate benefit they might otherwise confer. In theory, however, biofuels could be mass produced from a broader set of biomass feedstocks, each with its own supply chain, land use, and carbon emission implications. They most prominently include the land-intensive row crops mentioned above, but may also include dedicated energy crops, which are non-food crops that can be grown on marginal land for the specific purpose of providing biomass, such as switchgrass, miscanthus, bamboo, and wheatgrass. Agriculture crop residues, another form of biomass feedstocks, include the stalks and leaves of agricultural resources, including corn stover, wheat straw, and sorghum stubble. Residues may be used without affecting food production, provided that their removal from the landscape does not negatively impact soil productivity. Various types of forestry materials are also used as biomass feedstocks, resulting in a wide array of net climate impacts. These include standing trees, unsellable tree components like limbs and tops from typical timber harvests, dead or diseased trees, and trees harvested to reduce the risk of fire and pest infestation. Waste, including municipal solid waste originating from residential and commercial garbage (with components such as yard trimmings, paper, plastics, and food waste), can be used while reducing the amount of waste that ends up in landfills. Finally, lipids-rich algae, including seaweed and cyanobacteria, can be grown in ponds and biorefineries and converted into biofuels. Socioeconomic and environmental concerns about conventional biofuels made from row crops are driving interest in this wider set of biomass feedstocks, but the commercial viability, associated production emissions, and net climate impact of fuels made from unconventional (primarily waste-based) biomass feedstocks remain uncertain.

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45 Larson, E., et al. (2020). *Annex H of Net-Zero America: Potential Pathways, Infrastructure, and Impacts Report* (p. 3). Princeton University. https://netzeroamerica.princeton.edu/the-report

46 Larson, E., et al. (2020). *Annex H of Net-Zero America: Potential Pathways, Infrastructure, and Impacts Report* (p. 3). Princeton University. https://netzeroamerica.princeton.edu/the-report

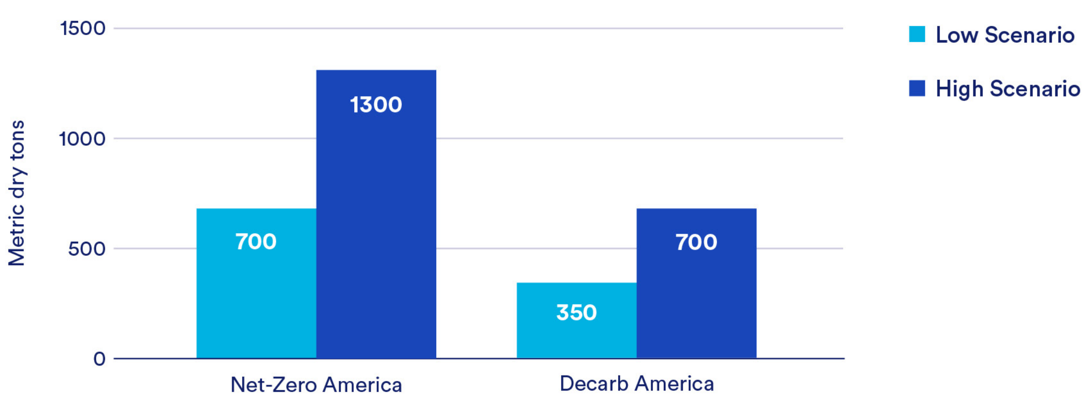
47 Office of Energy Efficiency & Renewable Energy. (2016). *2016 billion-ton report*. https://www.energy.gov/eere/bioenergy/2016-billion-ton-report

The Princeton report projects that by 2040, 4.2 quads (4.4 EJ) of biomass would be utilized annually under the low potential scenario and 11.3 quads (11.9 EJ) of biomass would be utilized annually in the high potential scenario.[48] By 2050, utilized biomass under the low potential scenario is 0.7 billion dry tonnes per year (13 EJ or 12.3 quads) and 1.3 billion dry tonnes per year (24 EJ or 22.8 quads) under the high potential scenario. (Both scenarios imply massive increases over current U.S. biofuel production, which stood at 1.39 quads (1.47 EJ) in 2019.) In both scenarios, all of the biomass assumed to be available would be fully utilized by 2050. In 2040, meeting domestic aviation energy demand with biofuels would require 86% of biomass assumed to be available under the low potential scenario (3.6 quads of the 4.2 quads of estimated biomass for utilization) or 32% under the high potential scenario (3.6 quads of the 11.3 quads of supply). In both scenarios, this represents a very high percentage of presumably available biomass and therefore biomass supply may not be sufficient to meet the demand for aviation biofuels in addition to the many other biomass uses envisioned in the Net Zero America study by 2040. In 2050, meeting domestic aviation energy demand with biofuels would require 33% of biomass assumed to be available under the low potential scenario (4.1 quads of the 12.3 quads) or 18% under the high potential scenario (4.1 quads of the 22.8 quads) — a less daunting prospect.

Table 4: Projected Biomass Utilization Needed to Meet Aviation Energy Demand With Biofuels

	2040		2050	
	Low scenario	High scenario	Low scenario	High scenario
Biomass utilized (quads)	4.2	11.3	12.3	22.8
Total biomass supply potential (billion dry tonnes)			0.7	1.3
Domestic aviation energy demand (quads)	3.6	3.6	4.1	4.1
Percent of available biomass utilization for aviation energy	86%	32%	33%	18%

Figure 5: Projected Biomass Supply in 2050



[48] Larson, E., et al. (2020). *Annex H of Net-Zero America: Potential Pathways, Infrastructure, and Impacts Report* (table 6). Princeton University. https://netzeroamerica.princeton.edu/the-report

Decarb America's Pathways to Net-Zero Emissions is another recent, U.S. economy-wide energy systems analysis and decarbonization study commissioned by CATF, Bipartisan Policy Center, and ThirdWay. Decarb America sees biomass as a significant contributor to reaching domestic net-zero emissions goals. Across modeling scenarios, the report expects production of 350 to 700 million metric dry tons of biomass annually by 2050, compared to 700 million to 1.3 billion dry tonnes under Net-Zero America estimates. Both reports expect biomass to be used primarily for hydrogen production, in part to produce zero-carbon fuels. Decarb America's lower modeled estimates of biomass production also indicate these volumes would be insufficient to fully displace conventional jet fuel with aviation biofuels.

Land-use and supply chain constraints for biofuels

The use of biofuel produced from dedicated feedstocks typically requires suitable land and massive quantities of water and nutrients. Biofuel production can have detrimental global land use impacts, contributing to the displacement of existing agriculture, food insecurity, and harming of biodiversity, as well as disruptions to existing carbon sequestration processes. An analysis by Goldman Sachs projected that renewable diesel production will require an additional 17 billion pounds of biomass feedstock, such as soybeans, creating a 13-billion-pound feedstock deficit as demand outstrips supply.[49] The analysis predicts this will create serious tension between demand for these feedstocks between biodiesel and food customers that will only be exacerbated by anticipated additional demand from aviation biofuel customers. It is important to evaluate land use implications as well as indirect impacts from dedicating land and feedstocks for biofuel production.

The degree of future biomass demand envisioned by Net Zero America and Decarb America relative to current biomass production is quite substantial. Increased production of biomass to meet the demand for sustainable aviation fuels would have significant implications, not just for biomass availability and land use, but also for supply chains.

Transporting biomass is typically more expensive on a dollar-per-btu basis than fossil fuels given its relatively-low energy density, and logistical considerations can add uncertainties and costs. Custom machinery may be required for harvesting and transporting biomass, processing the biomass may require substantial energy inputs, and significant storage space may be required. These considerations, particularly storage, are further complicated by the seasonality of biomass. Storage infrastructure may also need to address potential breakdown of biomass by bacteria and fungi. Cost-effective harvesting, processing, transporting, and storing of biomass feedstock at scale represents a significant challenge that has yet to be addressed in real world scenarios. Scale-up of biofuel production, to date, has only attempted to address these challenges based on modeled scenarios that may not meet real world conditions.

Biofuels also require further processing to become "drop-in ready." Biomass feedstocks typically contain high levels of oxygen which need to be removed. As mentioned in Part 1, this process of deoxygenation requires hydrogen inputs, elevating the hydrogen to carbon (H:C) ratio to the level of finished petroleum transportation fuels.[50] Some biomass feedstocks have a lower H:C ratio than traditional fossil fuels.[51] Scaling up biofuels will therefore require vast sources of hydrogen produced from low-emissions processes, creating new financial, environmental, and supply chain constraints that need to be considered.

Using biofuels to replace conventional jet fuels in the coming decades would necessitate an unprecedented scale-up of biofuel production, both globally and domestically. Doing so would require a substantial percentage of biomass to be converted to biofuels for SAFs, potentially at the cost of other potential uses for that biomass or the land on which it would be grown. Real world mass production of biofuels for the aviation sector will introduce a new series of challenges, from detrimental land- and water-use impacts to supply chain complications. It is therefore essential to consider the role of biofuel alternatives in decarbonizing the aviation sector.

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[49] Kelly, S. (2021, April 9). U.S. renewable fuels market could face feedstock deficit. *Reuters*. https://www.reuters.com/business/energy/us-renewable-fuels-market-could-face-feedstock-deficit-2021-04-09/

[50] Van Dyk, S., et al. (2019, January). *'Drop-in' biofuels: The key role that co-processing will play in its production*. IEA Bioenergy. https://www.ieabioenergy.com/wp-content/uploads/2019/09/Task-39-Drop-in-Biofuels-Full-Report-January-2019.pdf

[51] Van Dyk, S., et al. (2019, January). *'Drop-in' biofuels: The key role that co-processing will play in its production*. IEA Bioenergy. https://www.ieabioenergy.com/wp-content/uploads/2019/09/Task-39-Drop-in-Biofuels-Full-Report-January-2019.pdf

SECTION 4

Alternatives to Biofuels for the Aviation Sector

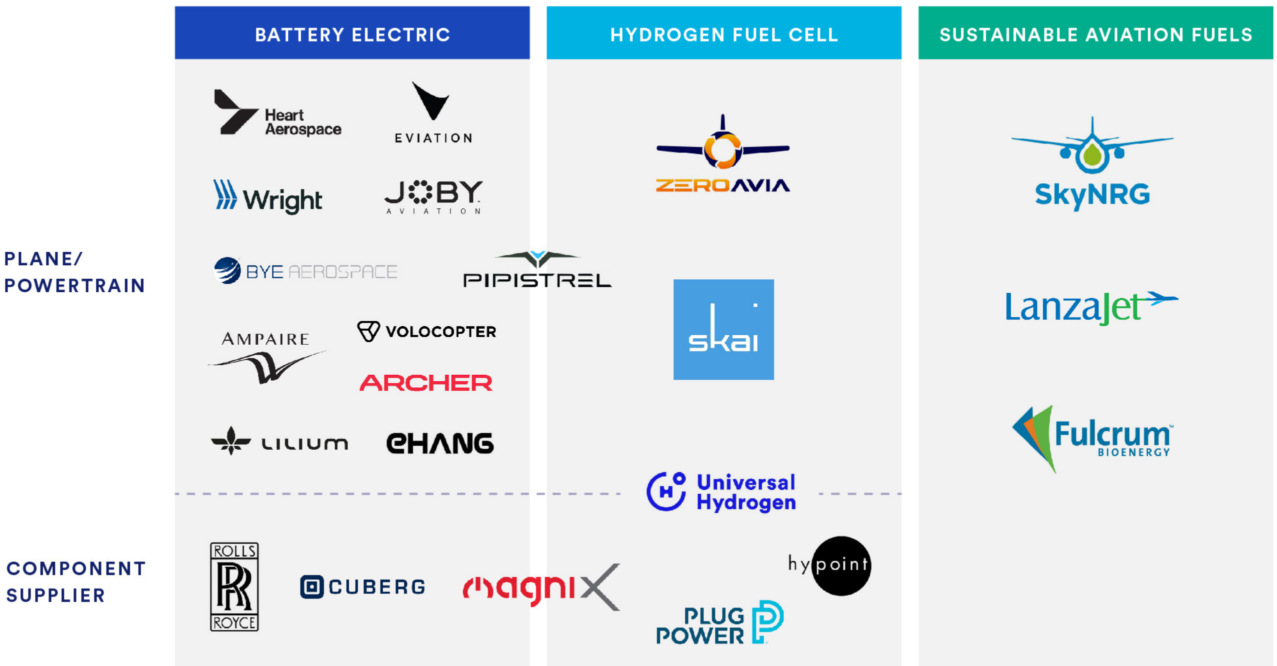
While biofuels are projected to play a large role in displacing conventional aviation fuel, there has been increasing interest and innovation in different aviation fuel options, including SZEFs (like hydrogen and synthetic fuels) and electricity. Figure 6, on the next page, shows active efforts in the private sector. Most of these technologies are at early stages in their development when it comes to readiness for the aviation sector relative to biofuels. This section covers the opportunities and challenges facing each of these alternatives, as well as other approaches to reduce aviation sector emissions.

Sustainable synthetic fuels

Synthetic fuels refer to drop-in ready aviation fuels that are made using CO_2 and hydrogen as feedstocks. For example, one of these processes involves splitting water into hydrogen through electrolysis using renewable electricity and then adding CO_2 captured from the atmosphere through DAC systems, and then combining the hydrogen and captured CO_2 to create synthetic kerosene. Currently, high costs are a significant barrier to adoption of these technologies. Separating CO_2 from ambient air currently requires significant amounts of electricity and heat (ideally, generated from low-carbon sources). While capturing CO_2 from point-source emission streams (e.g., from industries or power plants) potentially requires less energy, it would still cause a net increase in carbon emitted into the atmosphere because the process transfers geologic carbon to the atmosphere. Significant energy requirements and costs have limited this technology's potential to date. However, like some biofuels, synthetic fuels are drop-in ready, which means that they require little to no retrofitting of existing aircraft and are therefore typically considered SAFs. Further, given that biomass feedstock is not required, technologies like DAC-based fuels likely require significantly less land and water than biomass-based energy production

Figure 6: Companies Developing Alternative Technologies to Aviation Biofuels[52]

Source: 2021 Energy Impact Partners



processes.[53] Finally, using low-emissions hydrogen and DAC powered by clean energy may face fewer siting constraints, which in turn could reduce some geographic limitations and costly transportation requirements associated with aviation biofuels.

However, substantial investment in this technology would be necessary to achieve anything close to cost parity between sustainable synthetic and conventional jet fuels. Assuming renewable electricity could be available at $20 per MWh, synthetic fuels would be estimated to cost $1.10 per liter[54] compared to a high of $0.61 per liter for conventional jet fuel in 2021 (note that after Russia's invasion of Ukraine, conventional fuel costs reached a high of $1.28 per liter in May 2022).[55]

Electricity

With the decrease in battery technology costs and the rapid growth in battery electric vehicles, there has been growing interest in the electrification of aviation fleets. Commercial aircraft electrification offers benefits beyond reducing or eliminating CO_2 emissions; it can also eliminate contrails, as well as provide other environmental benefits including noise reductions. Electric motors have additional economic benefits, including potential savings on operational costs and longer life spans.[56]

While the potential of non-emitting aircraft is appealing, shifting to all-electric aircraft will require time due to

52 Freeman, M. (2021, March 15). *The runway for zero-carbon aviation*. Climate Tech VC. https://climatetechvc.org/the-runway-for-zero-carbon-aviation/

53 Creutzig, F. et al. (2019). The mutual dependence of negative emission technologies and energy systems. *Energy & Environmental Science,* 12(6), 1805-1817. https://doi.org/10.1039/C8EE03682A

54 Energy Transitions Commission. (2018, November). *Mission possible: Reaching net-zero carbon emissions from harder-to-abate sectors*. https://www.energy-transitions.org/publications/mission-possible/

55 Based on $2.30/gallon converted to liters, and high of $4.84/gallon converted to liters. Airlines for America. (n.d.). *Economic impact of commercial aviation*. Retrieved April 22, 2022, from https://www.airlines.org/impact/#daily-jet-fuel

56 Hamilton, K., & Ma, T. (2020, November 10). Electric aviation could be closer than you think. *Scientific American*. https://www.scientificamerican.com/article/electric-aviation-could-be-closer-than-you-think/

the technological hurdles involved. Further, without significant reduction in the size and weight of battery technologies, batteries are not feasible on larger aircraft for medium and long-distance flights. Even accounting for the higher efficiency of electric powertrains, today's batteries are about 14 times less energy dense than conventional jet fuel.[57] As a result, electric aircraft have been limited to smaller sizes with the largest electric plane flown to date being the 9-seater eCaravan with a range of only 100 miles.[58]

Hydrogen

Hydrogen fuel produces water vapor when combusted, and as a result, hydrogen-fuel-based propulsion eliminates CO_2 emissions in flight. Hydrogen fuel can be produced with minimal GHG emissions through electrolysis-produced hydrogen using renewable or nuclear electricity or fossil-produced hydrogen with carbon capture and upstream methane leak reduction.[59] Hydrogen fuel storage is lightweight relative to batteries and requires limited retrofits of existing smaller commuter and regional aircraft to transition them to hydrogen propulsion engines.[60] However, a joint study by the Fuel Cells and Hydrogen Joint Undertaking (FCH) and Clean Sky2 estimates that adopting hydrogen propulsion in short-range aircraft in 2040 would increase operating costs by 25% per passenger compared to conventional jet fuel aircraft.[61] This is primarily due to increased fuel costs, capital expenditures to retrofit aircraft for larger fuel tanks, higher maintenance costs, and fewer flight cycles due to longer refueling times. Economic and technological challenges compound as aircraft increase in size, requiring larger fuselages for liquid hydrogen storage, which require changes to the airframe design.[62] In addition to increased energy costs and retrofits, switching to hydrogen fuel will require new refueling infrastructure, development of reliable hydrogen supply chains, and new handling and safety regulations.[63]

Despite these challenges, there have been recent innovations in hydrogen-based commercial aircraft. One start-up, ZeroAvia, has retrofitted and tested a small aircraft with hydrogen fuel cells and predicts that by 2023, it will have developed engines that can power 10- to 20-seat aircraft flying up to 500 miles.[64] In 2020, Airbus revealed three concepts for zero-emission commercial aircraft relying on hydrogen as the primary power source capable of traveling more than 2,000 nautical miles that could enter service by 2035.[65]

Efficiencies and behavior change

Opportunities to decarbonize the aviation sector can be achieved partly through fleet and operational efficiencies, which have been leveraged to date to reduce fuel consumption in the aviation sector. Operational efficiencies involve reducing taxi time, more direct routing, and ensuring that aircraft match an optimal range or load. Conventional fleet efficiencies involve using composite material as seen in the Boeing 787 or Airbus 350, high aspect ratio wings, blended-wing body designs, and ultra-high bypass ratio turbofan engines that are currently in development. These fleet efficiencies could take over 10 years to develop and are estimated to reduce CO_2 emissions per revenue passenger kilometers by 1-2% annually through 2050. Nonetheless, these efficiency improvements could be

57 Adams, E. (2017, May 31). The age of electric aviation is just 30 years away. *Wired*. https://www.wired.com/2017/05/electric-airplanes-2/

58 Metcalfe, T. (2020, June 2). The largest electric plane yet completed its first flight — but it's the batteries that matter. *NBC News*. https://www.nbcnews.com/science/science-news/largest-electric-plane-yet-completed-its-first-flight-it-s-n1221401

59 Lewis, J. (2018). *Fuels Without Carbon: Prospects and the Pathway Forward for Zero-Carbon Hydrogen and Ammonia Fuels* (p. 8). Clean Air Task Force. https://www.catf.us/resource/fuels-without-carbon/

60 Fuel Cells and Hydrogen Joint Undertaking. (2020, May). *Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050*. https://doi.org/10.2843/766989

61 Fuel Cells and Hydrogen Joint Undertaking. (2020, May). *Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050*. https://doi.org/10.2843/766989

62 Kramer, D. (2020). Hydrogen-powered aircraft may be getting a lift. *Physics Today, 73*(12), 27. https://doi.org/10.1063/PT.3.4632

63 Fuel Cells and Hydrogen Joint Undertaking. (2020, May). *Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050*. https://doi.org/10.2843/766989

64 Cairns, R. (2020, October 23). This aviation startup is soaring ahead with hydrogen-powered planes. *CNN*. https://www.cnn.com/travel/article/zeroavia-zero-emission-hydrogen-planes-spc-intl/index.html

65 Airbus. (2020, September 21). *Airbus reveals new zero-emission concept aircraft*. https://www.airbus.com/en/newsroom/press-releases/2020-09-airbus-reveals-new-zero-emission-concept-aircraft

applied independent of fuel type.[66]

Behavior changes involve efforts to persuade travelers to reduce the frequency of air travel by replacing air travel with taking trains, buses, or personal vehicles where possible. European leaders have attempted to persuade travelers to take trains instead of airplanes for shorter distances,[67] and the French government recently banned short-haul domestic flights for trips that could be accomplished by train in less than 2.5 hours.[68] The COVID-19 pandemic forced behavior changes that stimulated significant reductions in business and conference travel and a shift to more virtual meetings. However, the durability of these recent changes remains in question as travel climbs back towards previous levels.[69]

Offsetting through nature-based solutions

ICAO's CORSIA was introduced by IATA and adopted by governments in 2016 to stabilize emissions from international air travel starting in 2021. The ICAO adopts standards as well as eligibility criteria and approves the allowable emissions units, or offset credits, that can be purchased to offset air travel emissions. As the only allowable market-based offsetting measure available for international flights, IATA estimates that CORSIA would save 300 million tons of CO_2 emissions by 2035.[70] While it is unclear the makeup of emissions offset projects that may be accepted through CORSIA (e.g., nature-based solutions, renewable energy development, etc.), it is likely that a significant portion of the offsets will be nature-based.

Involvement in CORSIA, however, is voluntary for countries until 2027, and the involved countries have not been fully publicized. The success of such a scheme is not only dependent on participation, but also on the integrity of the underlying offsets themselves (i.e., whether the carbon benefits are additional, measurable, permanent, and avoid leakage). While the initiative has attempted to establish criteria for high quality offsets, a report by Transport & Environment calls into question the robustness of the process and the ability to avoid double counting and highlights perverse incentives.[71] Systems like these are vulnerable to challenges like systematic over-crediting as highlighted in an analysis by CarbonPlan covering forestry offsets in California's offset program, resulting in significant overestimation of carbon abatement.[72] While some nature-based projects available through existing offset registries and mechanisms will not be eligible under CORSIA due to assessed permanence and leakage weaknesses, challenges still persist with nature-based solutions.[73] Tree planting efforts in seasonally snow-covered regions could contribute to the albedo effect, absorbing more incoming solar radiation and thereby offsetting climate benefits.[74] Mature native forests could be cleared for fast-growing plantation trees[75] and could require significant nitrogen fertilizer application that could cut into carbon sequestration benefits.[76] Given the large uncertainties with relying on nature-based solutions as offsets, relying on them

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66 At least in the context of conventionally-shaped aircraft designed to accommodate fuels that are compatible with current on-board fuel storage, delivery, and combustion systems.

67 Warren, H., et al. (2021, May 7). Europe asks travelers to ditch planes for night trains. *Bloomberg*. https://www.bloomberg.com/graphics/2021-europe-travel-night-trains-flights/

68 Willsher, K. (2021, April 12). France to ban some domestic flights where train available. *The Guardian*. https://www.theguardian.com/business/2021/apr/12/france-ban-some-domestic-flights-train-available-macron-climate-convention-mps

69 Chokshi, N. (2021, October 7). For airlines, it's looking more like 2019 again. *The New York Times*. https://www.nytimes.com/2021/07/22/business/airlines-united-american-southwest-delta.html

70 International Air Transport Association. (n.d.-c). *Offsetting CO2 emissions with CORSIA*. Retrieved April 22, 2022, from https://www.iata.org/en/programs/environment/corsia/#tab-2

71 Transport & Environment. (2019, September). *Why ICAO and Corsia cannot deliver on climate*. https://www.transportenvironment.org/publications/why-icao-and-corsia-cannot-deliver-climate

72 Badgley, G., et al. (2021). *Systematic over-crediting of forest offsets*. CarbonPlan. https://carbonplan.org/research/forest-offsets-explainer

73 Gehrig-Fasel, J., Gehrig, M., & Hewlett, O. (2021, April 23). *Nature-based Solutions in Carbon Markets.* Gold Standard Foundation. https://www.carbon-mechanisms.de/fileadmin/media/dokumente/Publikationen/Bericht/NbS_Carbon_Markets_2021_04_29_final_5515_.pdf

74 Popkin, G. (2019). How much can forests fight climate change? *Nature, 565*(7739), 280-282. https://doi.org/10.1038/D41586-019-00122-Z

75 Heilmayr, R., Echeverría, C., & Lambin, E. F. (2020). Impacts of Chilean forest subsidies on forest cover, carbon and biodiversity. *Nature Sustainability 2020 3:9, 3*(9), 701-709. https://doi.org/10.1038/s41893-020-0547-0

to achieve a large portion of decarbonization goals — as CORSIA envisions — carries substantial risks.

Carbon removals through direct air capture

Another option for addressing aircraft emissions is through DAC with carbon storage, for the purpose of offsetting emissions from the use of conventional jet fuel. DAC uses large fans to move large volumes of air to capture atmospheric carbon and store it securely underground. DAC has the theoretical potential to capture and permanently store the volume of CO_2 released by traditional aircraft, effectively negating in-flight CO_2 emissions, and this could become part of a prime decarbonization pathway using carbon removal for the industry in the long term. A benefit of DAC is that it can remove CO_2 measurably and permanently, with a smaller land-use footprint than some other decarbonization tools. DAC's land-use footprint, however, will vary widely based on the source of clean electricity, and more clean, firm, dispatchable power sources will be needed to ensure that DAC does not create environmental issues.

The chief hurdle that DAC must overcome to scale quickly is that it is a relatively new, high-cost technology with significant energy requirements that can limit its potential, and it will need technology-specific innovation incentives as well as enhancements to existing policies to reach scale. Also, when used as a mechanism for indirectly *offsetting* carbon dioxide emissions from the aviation sector, rather than as a tool for producing synthetic jet fuel (see "Sustainable synthetic fuels," above), reliance on DAC to lower net emissions could expose the aviation sector to the uncertainty and confusion that undermines other carbon offset approaches. Given the challenges to quickly scaling DAC, planning for significant portions of decarbonization to come from DAC could be risky. However, United Airlines recently partnered with the Canadian DAC company Carbon Engineering and project developer 1PointFive, to build the first industrial DAC plant in the United States with the capacity to capture and permanently sequester one million tons of CO_2.[77]

[76] European Academies Science Advisory Council. (2018, February). *Negative emission technologies: What role in meeting Paris Agreement targets?* https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_Report_on_Negative_Emission_Technologies.pdf

[77] United Airlines. (2019). *Fuel efficiency and emissions reduction*. https://www.united.com/ual/en/us/fly/company/global-citizenship/environment/fuel-efficiency-and-emissions-reduction.html

SECTION 5

Recommendations

Decarbonizing the aviation sector will involve a series of complex transitions. Global aviation demand is expected to rise in the medium- to long-term, despite the recent disruption caused by the COVID-19 pandemic. Today's aviation biofuel availability falls far short of the growing energy demand in the aviation sector over the coming decades. Meeting that energy demand with biofuels alone will require an unprecedented scale-up of biofuel production and will face significant barriers in terms of biomass availability, land-use implications, and supply chain challenges. This will necessitate biofuel alternatives, including SZEFs and potentially electric propulsion, that may require years to achieve commercial scale. The challenges associated with decarbonizing aviation described in this paper therefore must be met with coherent, ambitious policies that accelerate decarbonization efforts in the aviation sector, generate demand for low- and zero-carbon alternatives, and emphasize coordination and collaboration to multiply the impact of these policies.

Existing U.S. policies to decarbonize aviation

Policymakers in the U.S. are at the early stages of determining how to decarbonize the aviation sector. The current slate of supportive policies that exist are not particularly cohesive or aligned with a comprehensive aviation decarbonization strategy. Below are some of the *existing* policies that are supportive of aviation biofuels and decarbonizing air travel more broadly.

- The Inflation Reduction Act of 2022 (IRA) includes several measures intended to reduce emissions from the aviation sector. A competitive grant program for "Alternative Fuel and Low-Emission Aviation Technology" creates a $297 million fund for the development and deployment of SAFs and other technologies that target aviation emission reductions. The IRA also creates a blenders' tax credit (BTC) for SAFs through 2024 worth at least $1.25 per gallon to companies that blend SAF into the aviation fuel supply. To qualify, the SAF must achieve lifecycle GHG emissions that are at least 50% below the lifecycle emissions of conventional aviation fuel. The BTC includes a feature called the "applicable supplementary amount" that offers progressively more valuable tax credits for SAFs that achieve progressively deeper lifecycle greenhouse gas reductions; as such, the provision may steer investment toward fuels made from waste biomass and other feedstocks that have lower lifecycle GHG emissions. The IRA BTC also expressly broadens the definition of "sustainable aviation fuel" to encompass fuels made from non-biogenic feedstocks — including, for example, hydrogen-based fuels. After 2024, SAF producers can qualify for tax credits worth $0.35-$1.75 per gallon through a new feedstock-neutral Clean Fuel Production Credit (available through 2027).[78] Finally, the IRA also includes new or strengthened tax credits for low-emissions hydrogen and carbon capture and sequestration, respectively, which can be applied towards utilizing those technologies for the aviation sector.

- The Renewable Fuel Standard (RFS) is a national policy implemented by the U.S. Environmental Protection Agency (EPA) that requires a certain volume of biomass-based diesel, cellulosic biofuel, or advanced biofuel to replace or reduce the quantity of petroleum transportation fuel, including jet fuel.[79]
- In 2016, EPA found that GHG emissions from certain aircraft cause climate change and endanger public health and welfare.[80] And in 2021, EPA adopted the first ever GHG standards for certain new commercial airplanes, including all large passenger jets. The standards match the 2017 ICAO standards.[81] The Biden Administration is currently considering strengthening the standards under its Clean Air Act authority.[82]
- California's Low Carbon Fuel Standard (LCFS) was updated in 2019 to recognize SAFs as an eligible credit generator but did not include a compliance obligation on conventional jet fuel. SAFs generate credits by beating certain carbon intensity benchmarks; in 2019, however, SAFs generated less than 0.1% of the 14.8M credits in 2019.[83]
- The U.S. Department of Transportation (DOT) has embarked on a series of projects to improve air traffic management to reduce fuel use, test and evaluate new fuels, estimate aircraft emissions, and generate emissions inventories, and DOT is sponsoring research on the impact of non-CO_2 aviation emissions on the climate.[84]
- The U.S. Department of Agriculture (USDA) has made loan guarantees[85] to companies finding innovative ways to develop aviation biofuels through the Biorefinery Assistance Program.[86]
- DOE, DOT, and USDA launched a Sustainable Aviation Fuel Grand Challenge in 2021 to reduce the cost and accelerate deployment of SAFs primarily based on biofuels.[87]

While these existing policies are intended to benefit SAFs, they have historically underperformed. The International Council on Clean Transportation, a global research organization focusing on clean

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78 Pub. Law. No. 117-169 (amending 26 U.S.C. secs 40 and 45), 115-118, 180-186, 213-215, https://www.congress.gov/117/bills/hr5376/BILLS-117hr5376enr.pdf

79 U.S. Environmental Protection Agency. (n.d.). *Overview for renewable fuel standard*. Retrieved April 24, 2022, from https://www.epa.gov/renewable-fuel-standard-program/overview-renewable-fuel-standard

80 U.S. EPA. (2016, August 15). Finding Finding that Greenhouse Gas Emissions from Aircraft Cause or Contribute to Air Pollution, 74, Fed. Reg. 54, 422. https://www.federalregister.gov/documents/2016/08/15/2016-18399/finding-that-greenhouse-gas-emissions-from-aircraft-cause-or-contribute-to-air-pollution-that-may

81 U.S. EPA. (2021). *Control of Air Pollution From Airplanes and Airplane Engines: GHG Emission Standards and Test Procedures*. https://www.epa.gov/regulations-emissions-vehicles-and-engines/control-air-pollution-airplanes-and-airplane-engines-ghg

82 U.S. EPA. (n.d.). *Regulations for Greenhouse Gas Emissions from Aircraft.* https://www.epa.gov/regulations-emissions-vehicles-and-engines/regulations-greenhouse-gas-emissions-aircraft

83 Dell, J. (2020, May 14). Industry embraces new SAF pathway. *Argus Media*. https://www.argusmedia.com/en/news/2105455-industry-embraces-new-saf-pathway

84 U.S. Department of Transportation. (2017, February 27). *Federal programs directory: Programs and policies to reduce aviation emissions*. https://www.transportation.gov/sustainability/climate/federal-programs-directory-programs-and-policies-reduce-aviation-emissions

85 U.S. Department of Agriculture. (2014, September 4). *USDA announces loan guarantee to help innovative company turn waste into renewable jet fuel*. https://www.usda.gov/media/press-releases/2014/09/04/usda-announces-loan-guarantee-help-innovative-company-turn-waste

86 U.S. Department of Agriculture. (2020, January). *Biorefinery, renewable chemical, and biobased product manufacturing assistance program.* http://www.rd.usda.gov/programs-services/biorefinery-renewable-chemical-and-biobased-product-manufacturing-assistance

87 U.S. Department of Energy. (n.d.). *Sustainable aviation fuel grand challenge*. Retrieved April 24, 2022, from https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge

88 Petrenko, C., & Searle, S. (2018, October 18). *Is the renewable fuel standard enough to spur progress in advanced biofuels? Probably not*. The International Council on Clean Transport. https://theicct.org/is-the-renewable-fuel-standard-enough-to-spur-progress-in-advanced-biofuels-probably-not/

transportation policies and regulations, argues that the RFS has not done enough to attract private investment, while federal and state grant and loan guarantees have done much more to spur progress in biofuels.[88] Despite the recognition of SAFs as an eligible credit generator under California's LCFS, they have had limited traction given the more favorable economics associated with producing renewable diesel and the lack of a compliance obligation on conventional jet fuel within the LCFS.[89] Under the LCFS mechanism, some biodiesels or renewable diesels might generate more emissions reductions per dollar than SAFs, creating an opportunity cost to suppliers that produce SAFs instead of renewable diesels.[90] The production costs of aviation biofuels are several times higher than that of conventional jet fuel, and SAFs require greater energy and feedstock inputs than the equivalent production of renewable diesel.[91] Recently, efforts by the U.S. government to scale up use of SAFs has resulted in a "Sustainable Aviation Fuel Grand Challenge" that could promote biofuels that have little to no GHG savings relative to conventional fuels. An underlying Memorandum of Understanding between the federal departments of Energy, Transportation, and Agriculture sets a midcentury carbon intensity goal ("a minimum of a 50% reduction") that is only half as ambitious as it should be, fails to clearly define "sustainable aviation fuel," and sidelines the EPA despite its significant experience analyzing the lifecycle climate impacts of biofuels.[92] These examples emphasize the need for a stringent, comprehensive policy approach specifically designed to decarbonize aviation.

U.S. policy recommendations

Decarbonizing air travel will require a comprehensive policy response that overcomes a series of barriers the industry currently faces. These barriers highlight the need for policies supportive of a cohesive, broader government strategy to decarbonize the aviation sector. A comprehensive strategy would consist of two major policy objectives. The first objective would focus on non-biofuel options — namely, SZEFs (like synthetic fuels and hydrogen) and electric propulsion. The second objective, acknowledging a continuing role for aviation biofuels, would improve the supply and environmental performance of low-carbon aviation biofuels. This section outlines specific policy recommendations under these two policy objectives and suggests steps that can be taken for greater cohesion and collaboration across agencies and international bodies to accelerate progress.

89 Ghatala, F. (2020, April). *Sustainable aviation fuel policy in the united states: A pragmatic way forward*. Atlantic Council. https://www.argusmedia.com/en/news/2105455-industry-embraces-new-saf-pathway

90 Ghatala, F. (2020, April). *Sustainable aviation fuel policy in the united states: A pragmatic way forward*. Atlantic Council. https://www.argusmedia.com/en/news/2105455-industry-embraces-new-saf-pathway

91 Ghatala, F. (2020, April). *Sustainable aviation fuel policy in the united states: A pragmatic way forward*. Atlantic Council. https://www.argusmedia.com/en/news/2105455-industry-embraces-new-saf-pathway

92 U.S. Department of Energy, U.S. Department of Transportation, & U.S. Department of Agriculture. (2021). *Memorandum of understanding Sustainable aviation fuel grand challenge*. https://energy.gov/sites/default/files/2021-09/S1-Signed-SAF-MOU-9-08-21.pdf

U.S. policy objective 1: Development of SZEFs and electric propulsion technologies and their necessary infrastructure

A. Investments in research, development, and demonstration (RD&D)

I. Make RD&D investments, through DOE with the involvement of the research cooperative Aviation Sustainability Center (ASCENT) run by Washington State University and Massachusetts Institute of Technology, into:

1. SZEFs (including low-emissions hydrogen and synthetic fuels)
2. electric propulsion technologies

II. Make RD&D investments, coordinated through DOT's Office of Research, Development & Technology programs, into new aircraft design, including use of new composite materials, high aspect ratio wings, blended-wing body designs, and ultra-high bypass ratio turbofan engines to develop more efficient aircraft, or aircraft appropriately tailored for electric or hydrogen-based propulsion

B. Tax credits

I. Continue to create, strengthen, and improve production and investment tax credits for low-emissions hydrogen (ensuring applicability for use of hydrogen as a standalone aviation fuel or as part of synthetic aviation fuel), low-carbon intensity DAC that captures atmospheric CO_2 for use in synthetic aviation fuels, and the 45Q credit for carbon sequestration

C. Legislation, regulations, and other policy mechanisms to accelerate demand

I. Establish a zero-carbon aviation energy mandate, requiring an annual increase in the percentage of the domestic airplane fleet that is retrofitted for SZEFs or battery-electric propulsion (requires new legislation)

II. Develop a national and/or aviation-specific zero-carbon fuel standard (ZCFS) that applies to the aviation sector, and set increasingly stringent carbon intensity targets through the ZCFS (requires new legislation)

III. Require carriers to disclose information about the carbon intensity of flights and compare them to the carbon intensity of flights fueled with SZEFs or electric propulsion to increase awareness and demand for sustainable flights

IV. Require major government agencies, including the Department of Defense (DOD), to purchase a target percentage of SZEFs as part of their annual aviation fuel requirements

V. Establish a pooled procurement mechanism that carriers can use to more affordably procure SZEFs and electricity, potentially funded by fees applied to frequent flyers

VI. Explore the full breadth of the authority under the Clean Air Act for the executive branch to strengthen GHG emissions standards

D. Technical guidance, evaluation, and certification

I. Through the Federal Aviation Administration (FAA) Continuous Lower Energy, Emissions, and Noise (CLEEN) program, support efforts to evaluate and certify the life-cycle carbon intensity of newly developed fuels to determine how they affect aviation sector emissions, and help fuel producers navigate the testing process

II. Ensure regulations are in place through the FAA to comprehensively evaluate the safety implications, reliability, performance, and emissions reduction potential of new aircraft designs

U.S. policy objective 2: Improve the supply and environmental performance of low-carbon aviation biofuels

A. Investments in RD&D

I. Through the Department of Energy's Bioenergy Technology Office (BETO), provide RD&D grants to biofuel producers to:

1. explore region-specific biomass feedstocks that require low- or zero-land commitments, including fuels made from municipal wastes and other under-explored sources, to determine environmental impacts, cost-competitiveness, and viability of specific feedstocks
2. identify innovative ways to reduce land and water use requirements associated with producing biofuel feedstocks or to increase energy density of biofuels
3. address key supply chain constraints associated with the harvesting, production, transportation, and storage of biofuel

B. Tax credits

I. Establish a targeted blenders' tax credit that incentivizes the production of waste-based, low-carbon aviation biofuels, to help reduce cost discrepancies with conventional jet fuel[93]

II. Ensure that aviation biofuels with higher carbon intensities as determined by EPA do not qualify for blenders' tax credits to ensure investment is focused on low-carbon aviation biofuels

C. Regulations and policies to accelerate demand

I. Require major government agencies, including DOD, to purchase a target percentage of low-carbon aviation biofuels as part of their annual aviation fuel requirements

II. Establish a pooled procurement mechanism that carriers can use to more affordably procure low-carbon aviation biofuels funded by fees applied to frequent flyers

III. Require carriers to disclose information about the carbon intensity of flights and compare them to the carbon intensity of flights fueled with low-carbon aviation biofuels to increase awareness and demand for sustainable flights

D. Technical guidance, evaluation, and certification

I. Establish safeguards that ensure that aviation biofuels are made from feedstocks and processes that result in no or very low lifecycle CO_2 emissions.

Implementing these policy recommendations will require close coordination and collaboration between U.S. agencies, while accelerating global adoption will require targeted advocacy at the global level.
To achieve these goals, the executive branch should use existing authority to establish an office within DOE to coordinate and oversee the above-mentioned RD&D investments alongside EPA,[94] USDA, DOT, and other relevant departments. Internationally, the executive branch should also advocate through the ICAO for RD&D policies and demand incentives that improve the global production and demand of low-carbon aviation biofuels, SZEFs, and electric propulsion — all of which will be necessary to meet the global challenge of decarbonizing aviation by leveraging resources from around the world.

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[93] The Inflation Reduction Act of 2022 could represent progress in this direction.

[94] Involving the EPA is necessary given their substantial experience and expertise assessing and advising on carbon intensity and environmental implications of energy carriers. A recent memorandum of understanding between the Department of Energy, Department of Transportation, and the Department of Agriculture proposing an SAF grand challenge minimized EPAs involvement, creating the risk that biofuels with little to no carbon benefit or ecological benefits may qualify for this program (*see the MOU here: https://www.energy.gov/sites/default/files/2021-09/S1-Signed-SAF-MOU-9-08-21_0.pdf*).

Existing EU policies to decarbonize aviation

Like the U.S., total passenger air traffic has increased in the EU over the last several decades and is expected to increase by 21% in the 2015 to 2050 timeframe.[95] In response to this growing demand, the European Commission has used a number of mechanisms to address the aviation sector's GHG emissions, including:

- Inclusion of aviation CO_2 emissions in the EU Emissions Trading System (ETS), requiring all airlines operating in Europe to monitor, report, and verify emissions and surrender allowances against those emissions.[96] Thus far, free allowances have been provided to the aviation sector for their emissions, but these will be phased out under the currently proposed EU ETS revisions. For flights outside the EU ETS, existing policies call for the implementation of the CORSIA scheme through the ICAO.
- The Single European Sky (SES) regulatory framework (expected completion by 2030-2035)[97] to improve air traffic management performance and establish more efficient flight paths, which claims to reduce up to 10% of air transport emissions.[98]
- The Clean Sky Joint Undertaking (CSJU) — a public-private partnership between the European Commission and industry with the aim of demonstrating that by 2030, new technologies can reduce GHG emissions by at least 30% compared to 2020, with the goal of deploying these technologies by 2035.[99]

To date, almost all of Europe's aviation sector fuel consumption is fossil-based kerosene which will need to be addressed to reach the EU's "Fit for 55" goal of reducing economy-wide GHG emissions by 55% by 2030 and reducing transport emissions by 90% by 2050.[100]

The ReFuelEU Aviation proposal establishes a SAF blending mandate directed at fuel suppliers and applied to all flights departing EU airports. This volume-based mandate would require a minimum volume percentage of SAFs in the aviation fuel supply starting at 2% in 2025, increasing to 5% in 2030 (with a sub-mandate of 0.7% for synthetic fuels), and reaching 63% in 2050 (with a sub-mandate of 28% from synthetic fuels).[101]

This regulation is an effort to harmonize rules for SAF adoption across the EU, replacing existing national SAF mandates while allowing individual member states to introduce policies that would further accelerate SAF uptake. The proposed regulation has received positive attention for excluding food and feed-crop based biofuels, and instead relies on wastes, residues, and synthetic fuels. It imposes limits on airlines from uplifting more jet fuel than is needed to avoid higher fuel costs at destination airports and requires EU airports to create infrastructure necessary for the delivery and storage for SAFs.

EU policy recommendations

The ReFuelEU Aviation proposal represents a potentially significant leap in the adoption of SAFs in the airline industry. However, analysis by Transport & Energy (T&E) indicates that the proposed regulation overestimates the availability of waste-based biofuel feedstocks that do not have significant market or environmental impacts and suggests a cap on lipid-based feedstocks that have competing uses elsewhere which could cancel out additional GHG savings.[102] T&E estimates that appropriate waste-based biofuels could realistically only supply 10.3% of the estimated fuel demand and lipid-

95 European Commission's Directorate-General for Climate Action. (n.d.). *Aviation and the EU ETS*. Retrieved April 24, 2022, from https://ec.europa.eu/clima/eu-action/european-green-deal/delivering-european-green-deal/aviation-and-eu-ets_en

96 Tuominen, M. (2021, December). *Initial Appraisal of a European Commission Impact Assessment: "Fit for 55" legislative package: ReFuel EU Aviation*. European Parliamentary Research Service. https://ec.europa.eu/clima/eu-action/european-green-deal/delivering-european-green-deal/aviation-and-eu-ets_en

97 European Parliament. (2022). Air Transport: Single European Sky. https://www.europarl.europa.eu/factsheets/en/sheet/133/air-transport-single-european-sky#_ftn3

98 European Commission. (2020, September 22). *Single European sky: For a more sustainable and resilient air traffic management*. https://ec.europa.eu/commission/presscorner/detail/en/IP_20_1708

99 Clean Aviation Joint Undertaking. (2021). Strategic Research and Innovation Agenda (p. 5). https://clean-aviation.eu/sites/default/files/2022-01/CAJU-GB-2021-12-16-SRIA_en.pdf

100 European Commission's Directorate-General for Communication. (n.d.). *Clean aviation joint undertaking*. Retrieved April 24, 2022, from https://european-union.europa.eu/institutions-law-budget/institutions-and-bodies/institutions-and-bodies-profiles/clean-aviation-joint-undertaking_en

101 European Commission. (2021). *Proposal for a regulation of the European parliament and of the council on ensuring a level playing field for sustainable air transport.* https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52021PC0561

102 Transport & Environment. (2021, November). *ReFuelEU aviation: T&E' s recommendations*. https://www.transportenvironment.org/wp-content/uploads/2021/11/ReFuelEU-position-paper-1.pdf

based biofuels could supply 1.1% of the estimated fuel demand by 2050 — leaving synthetic fuels to supply the remaining 89% of the demand.

This potential supply-side challenge, among others, suggests there is still room to improve policies to decarbonize the aviation sector in Europe. First, the EU should consider addressing potential supply chain constraints and high prices associated with aviation biofuels and SZEFs. Second, greater investment is needed in alternative low-carbon aviation fuels. This otherwise ambitious regulation risks facing significant bottlenecks and falling short of its decarbonization potential without the complementary policies outlined below.

EU policy objective 1: Address potential supply chain and cost constraints associated with low-carbon aviation biofuels and SZEFs

- Provide RD&D grants to biofuel producers to:
  - Explore new non-food and crop-based feedstocks that require low- or zero-land and water commitments
  - Identify innovative ways to reduce land and water use requirements associated with producing biofuel feedstocks, or to increase energy density of biofuels
  - Address key supply chain constraints associated with the harvesting, production, transportation, and storage of biofuel
- Provide RD&D grants to lower the cost, reduce the energy footprint, and improve the performance of DAC technologies used in the production of synthetic aviation fuels
- Establish contracts-for-differences (CfD) programs for low carbon intensity DAC technologies that capture atmospheric CO_2 for use in SZEFs like synthetic fuels
- Provide development capital or loan guarantees necessary to de-risk the creation of aviation biofuel and synthetic aviation fuel plants. The Clean Skies for Tomorrow report estimates that public investment for new SAF plants could be in the order of 120 billion Euros over the next 15 years[103]
- Mandate preferential biomass feedstock access to the aviation sector
- Manage overall passenger demand for air travel through taxation of traditional jet fuel, applying surcharges to frequent flyers, and incentivizing other modes of transportation such as rail, which has been actively promoted by the EU in recent years. T&E envisions the ReFuel EU targets could be potentially achieved in part by reducing aviation fuel demand by almost half in 2050

EU policy objective 2: Invest in alternative low-carbon aviation fuels

- Provide RD&D grants on a Member State and EU level to advance early-stage SZEF (including hydrogen and synthetic fuels) and electric propulsion technologies
- Make RD&D investments into new aircraft design, including use of new composite materials, high aspect ratio wings, blended-wing body designs, and ultra-high bypass ratio turbofan engines to develop more efficient aircraft, or aircraft appropriately tailored for electric or hydrogen-based propulsion
- Recognize the use of low-emissions hydrogen or electric propulsion under the ReFuelEU framework
- Phase out the provision of free allowances to the aviation sector under the EU ETS as soon as feasible, and invest the resulting funds acquired in supporting the development of SZEFs, low-carbon aviation biofuels, and electric propulsion options
- Establish a policy mechanism such as CfD to incentivize the production of low-emissions hydrogen, ensuring applicability for use of hydrogen as a standalone aviation fuel

[103] World Economic Forum. (2021, July). *Guidelines for a sustainable aviation fuel blending mandate in Europe*. Clean Skies for Tomorrow. https://www3.weforum.org/docs/WEF_CST_EU_Policy_2021.pdf

SECTION 6

Conclusion

Decarbonizing the aviation sector demands an entirely different and more ambitious approach than has been taken to date. It requires policies that make the research, development, and deployment investments to commercialize new zero-emission propulsion technologies. Acknowledging a continued role for aviation biofuels, it will also require policies that improve the supply and environmental performance of low-carbon and waste-based aviation biofuels.

Ultimately, to drive the innovation necessary to fully eliminate the aviation sector's contributions to climate change, a cohesive and inclusive national and global strategy focused on the deployment of low-carbon aviation biofuels, SZEFs, and electric propulsion will be required, rather than a strategy focused solely on scaling up what constitutes SAFs today.

ICAO President Salvatore Sciacchitano remarked that "the introduction of radical, disruptive technology" will be needed to decarbonize aviation.[104] CATF intends to continue to investigate the opportunities, challenges, and scalability potential of what is envisioned to make up SZEFs (like hydrogen), battery electric propulsion, and other emerging decarbonization options in this rapidly evolving sector.

[104] Adler, K. (2021, November 10). COP26: Nations come together to promote aviation decarbonization. *IHS Markit*. https://cleanenergynews.ihsmarkit.com/research-analysis/cop26-nations-come-together-to-promote-aviation-decarbonization.html