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Navigating Sustainable Skies: Challenges and Strategies for Greener Aviation

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Report 24-07
April 2024

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Acknowledgements

We are grateful to Anna Stratton, Beia Spiller, Billy Pizer, Dan Shawhan, Divya Sanghi, Jingran Zhang, Mike Toman, Sebastian Eastham, Xuan Teng, Yongjoon Park, and individuals at Joby Aviation and United Airlines for their invaluable input, comments, and suggestions. All errors are our own.

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Abstract

Aviation, crucial for global connectivity, significantly contributes to climate change, accounting for 2.5 percent of human-induced CO_2 emissions and 3.5 percent of overall human-made changes to the energy balance in the Earth's atmosphere. The sector's CO_2 emissions have doubled since the mid-1980s, with projections indicating a potential tripling of demand by 2050, underscoring the urgency of greener solutions to balance economic benefits with environmental impacts. However, challenges abound, such as the high costs and sustainability concerns of sustainable aviation fuel, the limited capabilities of alternative technologies, such as hydrogen and electric aircraft, and the need for extensive infrastructure and international collaboration. The report offers an overview of different alternatives for greener aviation and the associated challenges, discusses policy approaches, and highlights areas for future research to effectively reduce the sector's environmental footprint.

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Executive Summary

This report offers an overview of sustainable aviation, focusing primarily on commercial aviation while also addressing a wide range of other aviation operations. It outlines challenges, strategies, and policy efforts for greener aviation in the United States and globally. Importantly, it identifies key research areas for policy development, serving as an introductory guide for researchers interested in aviation sustainability.

Environmental Impacts of the Aviation Industry

Commercial aviation is estimated to account for about 3.5 percent of the overall human-made changes to the energy balance in the Earth's atmosphere. One-third of this impact is estimated to come from CO_2 emissions and the rest from non-CO_2 factors, such as nitrogen oxides (NO_x) and contrails—the long, thin clouds that often form behind an airplane in cold and humid conditions that trap atmospheric heat. Alarmingly, CO_2 emissions from aviation have doubled since the mid-1980s and could account for a quarter of the CO_2 budget to limit warming to 1.5°C by 2050. Near airports, aircraft operations elevate pollutants, such as NO_x and ozone, adversely affecting air quality and human health. Moreover, airport operations and expansions often increase noise pollution in nearby neighborhoods. Finally, lead emissions from older, small piston-engine aircraft used in smaller non-commercial operations are the largest lead source in US air and present significant health risks.

Challenges

Scaling sustainable aviation technologies: In conventional aircraft, fuel economy can be improved through technological means, such as aerodynamic design, advanced engines, and weight reduction. Airline operations also contribute to efficiency through optimized flight routes, altitude and speed management, and reduced runway idling. However, despite these improvements, emissions from conventional aircraft are rising due to increasing air traffic.

In the near to medium term, sustainable aviation fuel (SAF) offers a viable greener alternative to traditional jet fuel. It is compatible with current aircraft and can reduce greenhouse gas emissions by up to 100 percent and contrail formations by 50–70 percent while also improving air quality compared to traditional jet fuel. SAF is produced from various raw materials, such as fats, oils, sugars, municipal waste, and captured CO_2, employing distinct pathways such as hydroprocessed esters and fatty acids (HEFA), Fischer-Tropsch (FT), alcohol-to-jet (ATJ), and power-to-liquid (PtL). Despite this diversity, SAF production currently falls short of global demand. A major challenge for agricultural feedstock is indirect land use change (ILUC), with concerns of deforestation and habitat destruction associated with cultivation. Edible crops like corn could further influence food prices. Accurately assessing the environmental impact of feedstocks and production methods is also challenging due to differences in models such as the International Civil Aviation Organization (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and Argonne Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET).

Feedstock availability is a significant hurdle, especially for HEFA feedstocks such as waste oils, which are inherently limited. While agricultural feedstocks could theoretically be expanded, competition from sectors like renewable diesel poses challenges. Emerging PtL technology—utilizing abundant water and CO_2—offers a solution. However, the early-stage and energy-intensive nature of the production process leads to high production costs. Moreover, its environmental benefits hinge on sustainable sourcing (e.g., renewable electricity for the electrolysis of water).

The financial landscape for SAF is challenging, with high production costs and market risks deterring private investment and making renewable diesel more appealing for producers. Government support and clear incentives are crucial for its economic viability. Additionally, the infrastructure for distribution and blending with conventional jet fuel requires further development. Finally, the low aromatic hydrocarbon content in SAF presents a dual aspect: it is an opportunity for reducing emissions, a significant environmental benefit, but simultaneously a challenge, as it can compromise seal integrity in older aircraft engines, necessitating new, compatible seal technologies.

In the longer term, hydrogen and electric aircraft may also help meet the aviation industry's sustainability and environmental goals. However, both face distinct challenges. Most importantly, they have lower passenger capacity and range than conventional aircraft due to the lower energy density of alternative fuels compared to kerosene, though hydrogen aircraft have an edge over electric counterparts.

Using hydrogen, in combustion engines or fuel cells, significantly reduces carbon emissions and other air pollutants. For storage, aircraft rely on liquid hydrogen, which is space efficient but requires advanced cryogenic technology, or compressed hydrogen gas, which is less efficient and requires high-pressure systems. The International Council on Clean Transportation (ICCT) estimates indicate that by 2035, liquid hydrogen could enable narrow-body planes to carry 165 passengers over 3,400 km and turboprops 70 passengers over 1,400 km, making hydrogen-powered flights commercially feasible. In 2018, about one-third of aviation CO_2 emissions originated from flights under 1500 km; ICCT's projections suggest that hydrogen aircraft could potentially replace these emissions long-term.

Key challenges in their deployment include safety concerns, mixed public perception due to historical risks, and extensive infrastructure needs for hydrogen storage and handling. Refueling with passengers onboard may not be feasible, adding to airport operational costs. Producing and delivering hydrogen is also costly and complex, with higher costs for cleaner hydrogen. Moreover, ensuring environmental justice in deploying hydrogen solutions is essential to address disparities in the hydrogen value chain. Hydrogen aircraft could also increase contrail formation, impacting climate change. Finally, scaling up requires collaboration across various sectors.

Electric aircraft, on the other hand, have zero in-flight emissions and lower maintenance needs but are severely constrained by battery technology. This limitation affects their range and payload, confining them to very short flights. ICCT estimates indicate that even if battery technology improved to double its current efficiency, electric planes seating around 90 passengers may only cover distances up to 280 km. This limited range means they would have a minimal effect on aviation's climate impact. However, they could still improve air quality by reducing the number of jet-fueled flight departures. Widespread adoption requires advanced charging infrastructure and potentially major power grid upgrades. Their environmental benefits also rely on whether the energy for charging them comes from renewable sources. Recent advancements are making short-range urban flights feasible, with studies suggesting electric vertical takeoff and landing aircraft could reduce emissions more effectively than electric cars for short distances.

Hybrid aircraft technologies, which utilize a combination of energy sources in flight are emerging as a promising solution. More developed than solely electric or hydrogen-powered alternatives, these technologies can be more readily adapted to fit current aircraft designs.

Voluntary changes in passenger behaviors: Another challenge is persuading passengers to make sustainable choices, such as rail, carbon offset programs, or flights with lower emissions. Many prefer air travel for its speed and convenience, even for short distances, despite the availability of greener alternatives. Encouraging a shift to rail for shorter trips involves improving its infrastructure, competitive pricing, and raising public awareness, which can be costly and complex. Carbon offsets provide an alternative, but their effectiveness is debatable due to validation challenges and potential community impacts. Moreover, getting passengers to choose lower-emission flights is complicated by inconsistent information from various flight comparison sites and the lack of a standardized emissions calculation method.

Operations and management: Efforts to improve aviation operations, such as optimizing flight schedules and engine settings, can further help reduce emissions but require a delicate balance between minimizing air quality impacts, cutting CO_2 emissions, and maintaining passenger satisfaction. Research shows that reducing CO_2 emissions can sometimes increase population exposure to other pollutants. Additionally, efforts to reduce CO_2 emissions by flying slower can lead to longer flight times, potentially impacting passenger experience. Finally, decarbonizing airport ground operations, such as by electrifying ground support equipment and shuttle buses and improving the energy efficiency of airport buildings, can further help reduce this industry's impact but requires comprehensive grid infrastructure upgrades, financial investment, technological innovation, sustainable energy sources, operational changes, training, and supportive policies.

Unclear national responsibilities: Under the United Nations Framework Convention on Climate Change (UNFCCC), emissions from international flights are recorded separately from individual countries' national totals. Instead, they are classified under "bunker fuels" due to their occurrence in international waters or airspace, complicating efforts to hold specific nations accountable. During the development of the 1997 Kyoto

Protocol, countries agreed to address emissions from these bunkers through the ICAO negotiations and not through the UNFCCC. Whether causal or not, this allowed countries listed as Annex I Parties to increase their emissions from these sectors without impacting their emission reduction commitments. For example, US aviation bunker fuel emissions doubled from 1990 to 2019.

Although the 2015 Paris Agreement encompasses all anthropogenic emissions, its lack of specificity has resulted in nationally determined contributions (NDCs) submitted by parties primarily focusing on domestic emissions, leaving international transport largely unaddressed.

CORSIA, introduced by ICAO in 2016, aims to manage emissions from international aviation, focusing mainly on airlines. However, effective emission reduction requires stakeholder involvement beyond just airlines, underscoring the need for countries to be responsible for these emissions.

Policy Solutions

Policies to promote the production and usage of SAF: Financial incentives, such as grants and tax credits, can reduce high production and usage costs, supporting feedstock cultivation, infrastructure, and research and development (R&D). Examples of such support include the US Department of Energy's loan guarantees for commercial-scale SAF projects and the tax credits for SAF under the Inflation Reduction Act (IRA).

Market-based strategies, such as the European Union's emissions trading system and ICAO's CORSIA, can encourage airlines to use SAF. This approach can also indirectly promote developing more fuel-efficient aircraft by increasing demand.

Government investment in R&D can foster SAF innovation, efficiency, and scalability, making it more viable for the industry. A notable example is the governmentwide SAF Grand Challenge by the US Departments of Energy, Transportation, and Agriculture and other federal agencies launched in 2021 to help reduce costs and expand production and use of SAF.

Mandates that require blending SAF with conventional fuels can boost its attractiveness for airlines. An example is the EU SAF mandate approved in 2023 under the ReFuelEU Aviation initiative. Imposing taxes on fossil fuels can further incentivize the shift toward SAF.

Policies to advance aircraft technologies: Strict standards for aircraft emissions, such as those introduced by the ICAO for CO_2 and nonvolatile particulate matter (nvPM) emissions, can encourage aircraft manufacturers to invest in R&D to meet or exceed these benchmarks. Concurrently, government investment in R&D, through initiatives such as the US Federai Aviation Administration's (FAA) Continuous Lower Energy, Emissions and Noise and Eliminate Aviation Gasoline Lead Emissions Programs, can advance aircraft performance and reduce emissions.

Furthermore, government subsidies for R&D, demonstration, and deployment of emerging technologies, such as hydrogen and electric aircraft, can help bring these technologies to the market and improve their range and passenger capacity. They could be viable for short-haul travel and offer significant environmental benefits and reduced noise levels. Due to their early-stage development, they are likely to receive inadequate private investment, making government support essential. Yet, current US incentives for them lag behind those for ground vehicles, indicating a need for increased support in this sector.

Policies to change consumer behavior: Investing in high-speed rail can reduce air travel dependency for short-haul travel, provided it is competitively priced. Taxing air passengers, such as the UK Air Passenger Duty, can also encourage shifts to other transport modes. Furthermore, regulating the Voluntary Carbon Offset (VCO) market can help validate the authenticity and environmental benefits of carbon offset projects and aid buyers in comparing and understanding different carbon offset options. Finally, corporate policy changes, such as encouraging virtual meetings, opting for lower-emission transport, and limiting nonessential travel, can significantly reduce business travel's environmental impact.

Policies to build sustainable airports: Financial incentives for renewable energy, electric ground service equipment, and hydrogen and electric aircraft infrastructure can encourage airports to embrace sustainable infrastructure and practices, reducing carbon and noise pollution and improving air quality. Over the longer term, policy reforms could streamline environmental reviews under the National Environmental Policy Act to accelerate airport electric and hydrogen aviation infrastructure development.

Policies to promote countries' accountability: CORSIA and ICAO's long-term global aspirational goal for international aviation are steps forward in managing international air travel's environmental impact but do not assign emissions responsibility from international flights to countries. Including these emissions in the NDCs under the Paris Agreement is being discussed as a strategy for comprehensive accounting. The EU and its 27 member states already include emissions from outgoing flights in their NDCs. Environmental advocacy groups are pushing countries to revise their NDCs to cover all aviation emissions, although accurately attributing carbon emissions from international aviation to specific countries is a complex challenge.

Open Questions

Questions related to sustainable aviation technologies: Research can help determine the cost-effectiveness of modernizing versus retrofitting older aircraft and the optimal timing for fleet replacement, weighing the economic and environmental benefits of new aircraft against the impacts of production and disposal. It is also necessary to fully understand the effects of various emissions, including NO_x, CO_2, and particulates, the effectiveness of emission reduction technologies, how aircraft manufacturers respond to regulations (such as ICAO's standards), and the true impact of policies on aircraft fuel efficiency.

Research is also essential in answering questions centered around SAF. It can help identify and resolve bottlenecks in maintaining a consistent feedstock supply. A key area is optimizing resource allocation, given the competition for feedstock and biorefinery capacity between renewable diesel and SAF. It is also crucial to understand the infrastructure and financing requirements for integrating SAF into aviation and analyze how international and national regulations, incentives, and mandates affect SAF pricing, adoption, production, and ticket prices. Research is needed to investigate the holistic environmental impacts, including ILUC, of various feedstock and pathways.

Research can also develop strategies for deploying and scaling hydrogen and electric aviation by helping improve production, storage, and transportation; assessing competition for hydrogen across sectors and strategies for efficient distribution; assessing environmental justice issues across hydrogen value chain; and exploring infrastructure needs, including flight patterns, refueling strategies, network design, and the viability of hub-and-spoke systems. It can also evaluate the life-cycle environmental effects of different technologies and compare the costs and benefits with alternatives such as high-speed rail. As regulatory bodies, such as the Federal Aviation Administration and European Aviation Safety Agency, develop guidelines on new technologies, research can play a crucial role in shaping them. Finally, research can help assess consumer attitudes toward new aviation technologies to steer their development.

Questions related to consumer behavior: Understanding consumer behavior is crucial for shaping sustainable transportation policies. Research can highlight how factors such as pricing, comfort, and demographics influence transport choices and willingness to pay for sustainable aviation. These insights are vital for devising strategies that encourage consumers' shift toward greener aviation and alternative transportation. Research can also help assess the effects of policies such as aviation taxes and limits on short-haul flights on passenger behavior, ticket prices, and air travel demand; understand the role of loyalty programs in influencing flying frequency; and identify the impact of strategies, such as frequent-flyer taxes, on the travel habits of frequent flyers. Moreover, further research is needed to regulate VCOs to ensure they result in genuine, additional, and verifiable emission reductions.

Questions related to airport operations: The impact of airport operations on nearby populations, influenced by factors such as wind direction and flight frequency, is a key research area for mitigating adverse effects. Additionally, research can help optimize airport operations for environmental and passenger service improvements and develop ways to improve the setup of alternative technologies, such as hydrogen and electric aircraft systems.

Questions related to countries' responsibilities: The effective attribution of carbon emissions to individual countries is an open question. Research and policy engagement can help develop a globally accepted method to distribute carbon-offsetting responsibilities.

1. Introduction

Aviation offers an unparalleled means of connecting global communities in the modern age but is an important contributor to climate change. The aviation industry is estimated to contribute about 3.5 percent of the overall human-made changes to the Earth's energy balance (as measured using net anthropogenic effective radiative forcing (ERF)) (Lee et al. 2021).[1] Aviation emissions have increased twofold since the mid-1980s, consistently comprising 2–2.5 percent of global emissions.[2] Alarmingly, projections suggest that by 2050, aviation could be responsible for a quarter of the permissible CO_2 emissions to limit global warming to 1.5°C above preindustrial levels.[3] Considering the long lifespan of aircraft, up to 30 years, the urgency for immediate, decisive action is clear. Industry stakeholders and policymakers are tasked with developing and implementing strategies for long-term net-zero emissions to ensure a sustainable future.

In response, momentum is growing among various stakeholders toward sustainable aviation. At the international level, the International Civil Aviation Organization (ICAO)—a United Nations (UN) agency that helps foster collaboration among 193 countries—has targeted net-zero carbon emissions for global civil aviation by 2050.[4] The UN has also emphasized the imperative to curtail per capita CO_2 emissions to 2–2.5 tons per person by 2030 (UNEP 2020). Although this target is not directly aviation specific, reducing emissions from aviation is vital to it. For perspective, the ICAO Carbon Emissions Calculator[5] shows that one passenger flying economy from Los Angeles to London and back will generate about 880 kg of CO_2, 35–45 percent of the individual emission limits.

Several countries and industry players have their own plans for making this sector more sustainable. Denmark, Sweden, and Norway have all committed to phasing out fossil fuel–based domestic flights.[6] The US Biden administration introduced a sustainable aviation fuel (SAF) grand challenge with an ambitious target of 3 billion gallons by 2030. Adding a significant milestone to these efforts, in 2023, the European Union approved the world's largest SAF mandate as part of the ReFuelEU Aviation

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[1] These numbers likely underestimate the actual climate impact of aviation, as they do not consider emissions from ancillary sources related to aviation, such as ground transportation at airports. For more details, see **What is the True Climate Impact of Aviation | Treehugger**

[2] **Climate change and flying: what share of global CO_2 emissions come from aviation? | Our World in Data**

[3] **Analysis: Aviation could consume a quarter of 1.5C carbon budget by 2050 | CarbonBrief**

[4] **ICAO welcomes new net-zero 2050 air industry commitment | ICAO**

[5] **ICAO Carbon Emissions Calculator | ICAO**

[6] **Denmark to make domestic flights fossil fuel free by 2030 | BBC**

initiative.[7] Dominant aircraft manufacturers Boeing and Airbus have also announced sustainability goals.[8] An International Air Transport Association (IATA) report counted more than 130 relevant SAF projects announced by more than 85 producers across 30 countries.[9] Together, these efforts indicate a growing commitment to making aviation sustainable.

Nevertheless, addressing the sustainability challenges posed by aviation is particularly difficult for several reasons. The widespread adoption of SAF faces persistent hurdles, including the inadequate availability of necessary feedstock quantities—exacerbated by intense competition from other sectors, nascent state of fuel production pathways, sustainability concerns stemming from the expansion of agricultural feedstock production, and high cost of implementation. Additionally, alternative, longer-term technologies, such as hydrogen and electric aircraft have limited capabilities and demand substantial infrastructure investments, hampering their immediate viability. Moreover, given aviation's global nature, limited cross-country collaboration also impedes progress in addressing its impacts.

This report seeks to lay a foundational overview of sustainable aviation, briefly covering a wide range of topics within the field. Although its focus is on commercial aviation, it also encompasses a broad spectrum of other aviation activities. Each topic presented could be the focus of an in-depth study; however, the goal here is to provide a concise overview that outlines the main challenges, strategies, and policy directions being pursued both in the United States and internationally to promote sustainable aviation. We particularly focus on identifying key research areas that could inform effective policymaking to minimize aviation's environmental impact. This report is designed as a primer for those new to aviation sustainability, especially researchers looking for a comprehensive snapshot of current issues.

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[7] **EU approves world's largest sustainable aviation fuels mandate | Travel Tomorrow**

[8] **Sustainable Aerospace Together | Boeing.com**

[9] **SAF Production Set for Growth but Needs Policy Support to Diversify Sources | IATA**

2. Environmental Impacts of the Aviation Industry

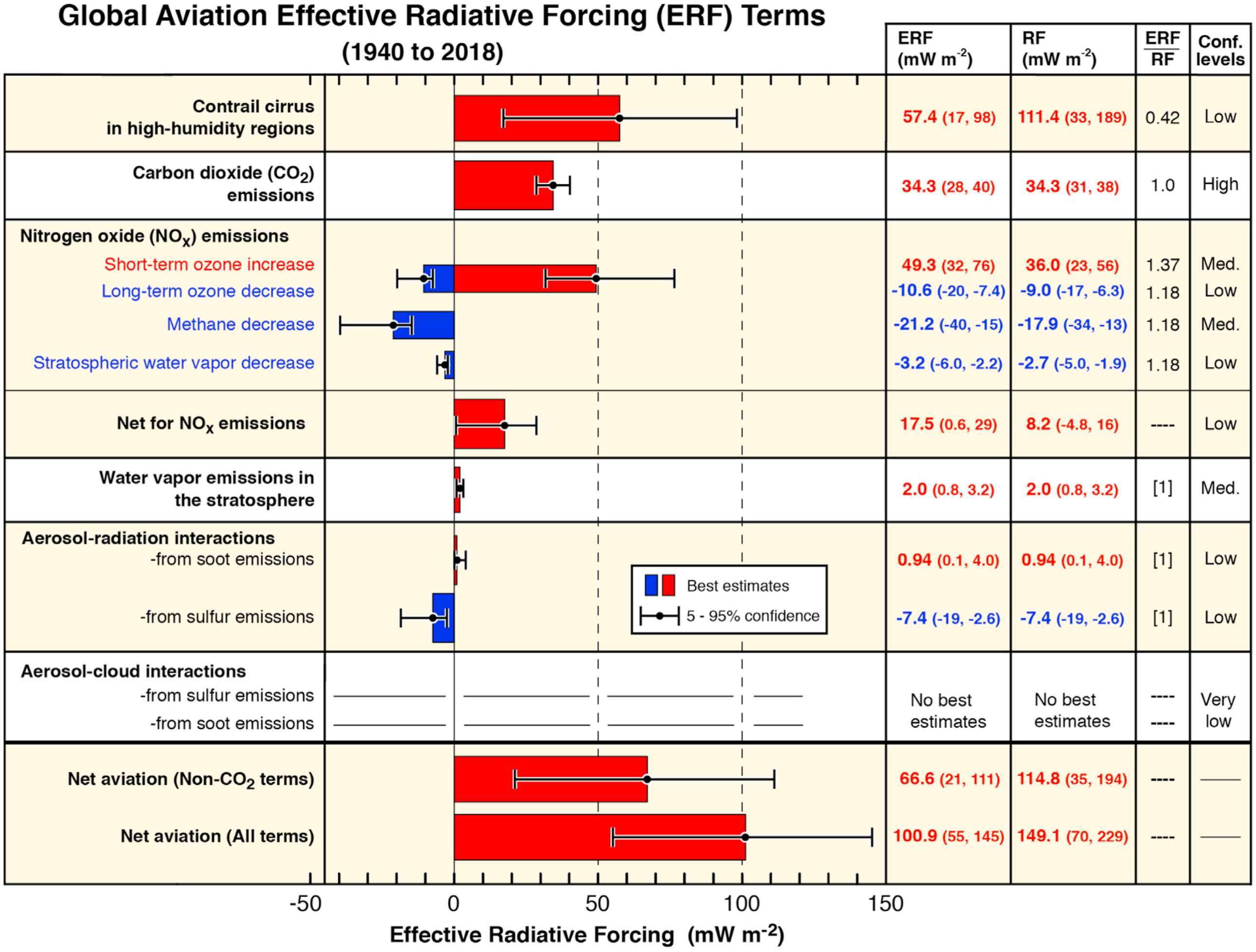
The aviation sector encompasses various activities, such as commercial passenger and goods transport, military operations, agricultural flights, and research missions, each using specialized aircraft designed for their unique needs. However, this sector, mainly commercial aviation, is an important contributor to climate change and poses health challenges by diminishing air quality and causing noise pollution in communities near airports. Disposing of hazardous materials from scrapped aircraft can further affect the environment. This section elaborates on these impacts.

Global warming impact: According to Lee et al. (2021), commercial aviation contributes about 3.5 percent (80.4 mW m^{-2}) to the Earth's total ERF—a metric indicating the extent of human impact on the climate. This impact is a result of various factors with differing climate effects. About one-third of it is due to carbon dioxide (CO_2) emissions from aircraft; the remaining two-thirds result from non-CO_2 emissions, including nitrogen oxides (NO_x), sulfur oxides (SO_x), various aerosols (nitrate and sulfate), water vapor (H_2O), soot, and contrails.

The role of non-CO_2 emissions is significant but also complex. The primary effect comes from contrails, which are long, thin clouds created in cold and humid conditions when water vapor condenses and freezes around small particles from the plane's engine, forming ice crystals that trap heat in the atmosphere. Studies, including Lee et al. (2021) and Jaramillo et al. (2022), indicate that they are responsible for 35–57 percent of aviation's warming impact. In contrast, nitrate and sulfate aerosols generated from NO_x and SO_x emissions, respectively, have a cooling effect (Prashanth et al., 2022). Despite the cooling effect from these aerosols, the non-CO_2 factors lead to a significant net warming effect.

Figure 1, derived from Lee et al. (2021), presents estimated climate impacts of different factors during 1940 to 2018, distinguishing between warming (red bars) and cooling (blue bars) effects. It provides the best estimates and their uncertainty ranges (5–95 percent confidence intervals) for ERF. It also includes numerical ERF and radiative forcing (RF) values in the columns with 5–95 percent confidence intervals and ERF/RF ratios and confidence levels. While RF measures immediate impacts from factors like CO_2, ERF includes broader effects over time, like changes in clouds and temperature, making it the preferred metric for evaluating climate impacts. The figure shows that the aggregation of non-CO_2 terms constitutes over half of the total aviation net ERF. Moreover, the uncertainty distributions (5 percent, 95 percent) illustrate that non-CO_2 factors contribute approximately eightfold more than CO_2 to the uncertainty in the aviation net ERF as of 2018. Given these uncertainties, assessing the overall impact of aviation on climate remains a complex task.

Figure 1. Climate Impacts of Global Aviation



	ERF (mW m^{-2})	RF (mW m^{-2})	ERF / RF	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO_x) emissions				
Short-term ozone increase	49.3 (32, 76)	36.0 (23, 56)	1.37	Med.
Long-term ozone decrease	-10.6 (-20, -7.4)	-9.0 (-17, -6.3)	1.18	Low
Methane decrease	-21.2 (-40, -15)	-17.9 (-34, -13)	1.18	Med.
Stratospheric water vapor decrease	-3.2 (-6.0, -2.2)	-2.7 (-5.0, -1.9)	1.18	Low
Net for NO_x emissions	17.5 (0.6, 29)	8.2 (-4.8, 16)	----	Low
Water vapor emissions in the stratosphere	2.0 (0.8, 3.2)	2.0 (0.8, 3.2)	[1]	Med.
Aerosol-radiation interactions -from soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
-from sulfur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions -from sulfur emissions -from soot emissions	No best estimates	No best estimates	---- ----	Very low
Net aviation (Non-CO_2 terms)	66.6 (21, 111)	114.8 (35, 194)	----	——
Net aviation (All terms)	100.9 (55, 145)	149.1 (70, 229)	----	——

Source: Lee et al. (2021)

Air pollutant emissions: Aircraft ground operations and landing and takeoff (LTO) phases increase the level of pollutants, such as NO_x, ozone (O_3), and fine particulate matter ($PM_{2.5}$), which diminish air quality in the vicinity of major airports and across broader regional areas (Quadros et al. 2020; Hudda et al. 2020; Masiol and Harrison 2014). LTO emissions contribute to premature mortality around major airports and, at the local scale, NO_2 health impacts were shown to outweigh $PM_{2.5}$ health impacts (Miake-Lye and Hauglustaine 2022).

More than 90 percent of NO_x emissions from aviation occur above 3,000 feet.[10] However, research indicates that these high-altitude emissions can affect the lower atmosphere, the troposphere, contributing to the formation of ground-level O_3 and particulate matter (PM). Emissions at cruising altitude are recognized as a significant

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[10] Impacts of Aviation NO_x Emissions on Air Quality, Health, and Climate | ICAO

source of both surface-level ozone, with a global increase of 0.3–1.9 percent relative to other emission sources, and $PM_{2.5}$, with an increase of 0.14–0.4 percent in regions with heavy air traffic (Miake-Lye and Hauglustaine 2022). These pollutants are a major contributor to aviation-induced premature mortality worldwide.

Additionally, NO_x could go to the higher atmosphere, the stratosphere, and destroy the ozone layer. This layer, different from the harmful troposphere ozone, is vital for shielding the Earth from the sun's ultraviolet radiation. Because of the abundance of ozone and lower atmospheric pressures, the concentration of atomic oxygen is sufficiently large that NO_x can catalytically destroy ozone.[11] Zhang et al. (2023) highlighted that introducing a supersonic aircraft fleet may result in a 0.74 percent decrease in the global ozone layer, or about 20 percent of the peak impact caused by chlorofluorocarbon emissions. Depleting the ozone layer causes an increased amount of ultraviolet radiation on Earth and increases the risk of skin cancers.[12]

Moreover, small piston-engine aircraft, such as the Cessna 172, contribute significantly to environmental issues due to their use of leaded aviation gasoline (avgas). Typically seating between 2–10 passengers and with an average age of 45–47 years, these planes are mainly used in non-commercial aviation sectors such as private transport, training, and recreational flying. The leaded avgas these aircraft use to prevent engine knocking is the foremost source of airborne lead in the US, surpassing 50 percent of total emissions since 2008. Leaded avgas consumed in the United States averaged around 196 million gallons annually from 2011 to 2020, highlighting the scale of this issue.[13] The adverse health effects of lead, especially on children, are well documented, including harmful and permanent neurodevelopmental consequences, such as lowered intelligence, impaired cognitive functioning, and a higher risk of attention deficit hyperactive disorder (Hong et al. 2015; Reuben et al. 2017; Rodrigues et al. 2016). No threshold value has been identified below which lead is deemed safe (Ruckart et al. 2021).

Noise impacts: Operating and expanding airports also often increase noise in nearby neighborhoods. ICAO predicted that in 2018, airplane noise affected approximately 16,486 square kilometers, impacting around 36.6 million people.[14] In addition, research has indicated that people are more bothered by aircraft noise than they were 30–40 years ago (Janssen et al. 2011). Numerous studies have also linked it to adverse health effects, including increased risk of hypertensive (Saucy et al. 2021; Schmidt et al. 2021) and ischemic (WHO 2019) heart disease. It has been shown to increase sleep disturbance (WHO 2019) and can impair children's cognitive development, with a 20 dB increase in exposure leading to a significant decrease in reading scores, equivalent to a delay of about two months (Klatte et al. 2017).

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[11] **Aviation and the Global Atmosphere | IPCC**

[12] **Health and Environmental Effects of Ozone Layer Depletion | US EPA**

[13] **Finding That Lead Emissions from Aircraft Engines That Operate on Leaded Fuel Cause or Contribute to Air Pollution That May Reasonably Be Anticipated To Endanger Public Health and Welfare | National Archives**

[14] **Environmental Protection—General provisions, Aircraft Noise and Local Air Quality | ICAO**

Aircraft end of life and recycling: The average lifespan of passenger aircraft is about 26.5 years, with an increasing trend in retirements in recent decades.[15] Often, economic factors lead to these early retirements; aircraft in good technical condition are sometimes more profitable when disassembled and sold for parts. The end-of-life process involves two main phases: removing reusable parts in compliance with aviation regulations and then dismantling and recycling, which results in revoked certification. This process poses environmental risks, as aircraft contain hazardous materials requiring careful handling during the latter phase, such as fuel, hydraulic oil, and specific components, such as emergency oxygen bottles. Older aircraft might contain depleted uranium, requiring careful disposal. However, a significant portion of an aircraft, approximately 85–90 percent by weight, can be reused or recycled. Less than 10 percent ends up as waste. Recycling technologies, especially for carbon-fiber materials, have advanced, although challenges remain for materials containing embedded flame retardants.

In the next sections, we explore the progress and challenges in mitigating aviation's environmental impact.

3. Challenge 1: Scaling Sustainable Aviation Technologies

In traditional fuel–based aviation, improving fuel efficiency is a vital strategy for reducing the industry's carbon footprint and improving public health outcomes by lowering air pollutant emissions, such as NO_x. Various methods exist; the primary approach involves technological improvements, such as improving aerodynamic design to reduce drag and fuel consumption, engine technology advancements, such as high-bypass turbofan engines, and weight reduction through materials, such as carbon-fiber composites.[16] Recent advancements in technology have led to notable improvements in fuel efficiency and reduced environmental impact. For example, the Airbus A350-900 and A320neo, Boeing 787 Dreamliner, Bombardier Cseries, and Embraer e195-e2, illustrate remarkable efficiency, due to lighter-weight materials, more efficient engines, improved aerodynamics, and advanced avionics.[17] Leading energy-efficient aircraft designs under development include high-aspect-ratio wings and blended-wing-body configurations.[18]

Another factor influencing emissions is the seating configuration. As first- and business-class seats typically occupy more cabin space than economy seats, airlines can lower carbon emissions per passenger by opting for more economy and fewer business-class seats.[19] Moreover, upgrading or retrofitting older aircraft can also lead to efficiency improvements. Finally, as detailed in Section 5, operational practices, such as optimized flight routing, altitude and speed management, and reduced runway idling, enhance efficiency.

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[15] **Best Practices and Standards in Aircraft End-of-Life and Recycling | ICAO**

[16] **4 Ways Changes In Aircraft Design And Components Reduce Fuel Consumption | Honeywell**

[17] **Top 5 Most Fuel-Efficient Airplanes in the World | GreenWorldwide**

[18] **Aircraft Technology Net Zero Roadmap | IATA**

[19] **A first-class way to reduce airline carbon emissions | New Scientist**

Despite the improvements in per-passenger emissions, fuel consumption is also heavily impacted by air traffic volume. A study by the International Council on Clean Transportation (ICCT) found that US commercial airlines improved their fuel efficiency by 23 percent between 2005 and 2019 but that total fuel burn and CO_2 emissions increased by 7 percent, largely driven by the rapid growth of low-cost carriers, whose traffic expanded faster than improvements in their fuel efficiency (ICCT, 2021). Future reductions in fuel consumption might be harder to achieve, as the aviation industry has already made easier improvements.[20]

In the near to medium term, SAF offers a more environmentally friendly option than traditional jet fuel, significantly reducing greenhouse gas (GHG) emissions, contrail formation, and air pollution during landing and takeoff. Made from diverse sources, SAF can be used in existing aircraft. Despite its benefits, production is limited due to several challenges: the sustainability of feedstocks, difficulties in accurately measuring environmental impacts, competition for feedstocks with other industries, high production costs, immature production processes, lack of financial backing, underdeveloped infrastructure for distribution and blending, and the need for new technologies to address the lower aromatic hydrocarbon content that affects seal integrity in older engines.

In the longer term, developing hydrogen, electric, and hybrid electric aircraft can also partly help meet the industry's sustainability and environmental goals. Hydrogen in combustion engines or fuel cells eliminates carbon emissions and greatly diminishes or removes other air pollutants. However, the environmental effectiveness largely hinges on the production methods. Similarly, electric aircraft are powered by batteries and have no direct airborne emissions during flight, but their total environmental impact depends on how the electricity for charging is sourced. Hybrid-electric aircraft combine traditional and electric propulsion, offering a significant cut in fuel use and emissions. These technologies also notably decrease noise pollution, leading to quieter surroundings, especially near airports. This reduction in both air and noise pollution can substantially lower health risks linked to aviation, highlighting the wide-ranging advantages of these technologies.

However, their widespread adoption faces key challenges, including their limited capacity and range, the need for specialized refueling or charging infrastructure, the coordination requirements among a range of stakeholders, and the evolving regulatory landscape. Hydrogen aircraft require solutions for safe, renewable, and cost-efficient hydrogen production, transportation, and storage, and electric aircraft demand extensive charging and electric grid infrastructure. We elaborate on these technologies and challenges next.

3.1. Sustainable Aviation Fuel

SAF is a greener alternative that provides a substantial environmental improvement over traditional jet fuel. Prussi et al. (2021) found that it can reduce greenhouse gas (GHG) emissions by up to 94 percent compared to its fossil-based counterpart. Voigt et al. (2021) found that SAF can reduce contrail formations by 50–70 percent at cruising altitudes. Moreover, Arter et al. (2022) demonstrated that 50 percent SAF blends can reduce $PM_{2.5}$ population-weighted concentrations by 18.4 percent and premature mortalities from LTO-attributable $PM_{2.5}$ emissions by up to 18 percent. Importantly, SAF can be used in existing aircraft without modifications, making it a viable option for greener aviation.

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[20] **Fuel efficiency: Why airlines need to switch to more ambitious measures | McKinsey**

The production of SAF begins with various raw materials like fats and oils, sugars and cereals, municipal solid waste, wood and agricultural residues, or water and non-fossil CO_2. These materials are transformed into SAF through distinct technological pathways, each requiring approval by the American Society for Testing and Materials (ASTM) prior to commercial use. Some pathways can accommodate various types of feedstocks, and some feedstocks can be utilized in multiple pathways. The choice of feedstock and the pathway influences the SAF's chemical composition and determines its allowable blending limit with conventional jet fuel, which can vary from 5 to 50 percent.

Among the pathways, hydroprocessed esters and fatty acids (HEFA) is the most established. It converts fats and oils into jet fuel and has been approved by ASTM for blending up to 50 percent with conventional jet fuel since July 2011.[21] Fischer-Tropsch (FT) technology, which converts woody biomass into gas and subsequently into fuel, received approval for a similar blend ratio in June 2009. Alcohol-to-jet (ATJ) technology, converting alcohol into fuel, was approved for isobutanol conversion in April 2016 and for ethanol conversion in June 2018, allowing for blends of up to 30 percent. Power-to-liquid (PtL) is an emerging technology. It uses renewable electricity for hydrogen generation and non-fossil CO_2 and results in what is known as "e-fuel", offering possibly up to 100 percent GHG reduction.[22]

Despite this diversity, SAF production and deployment have been low. As of 2022, global production was 300–450 million liters (80–120 million gallons), a mere 0.1–0.15 percent of global jet fuel demand.[23] US production was 15.8 million gallons in 2022, not even reaching 0.1 percent of the total fuel consumed by US airlines. This falls starkly short of the Federal Aviation Administration (FAA) target for US airlines to use 1 billion gallons of SAF annually by 2018.[24] However, in 2023, global SAF volumes exceeded 600 million liters (~160 million gallons), doubling the previous year's production and indicating a positive trend.[25] The outcomes of COP28, which underscore the global call to transition away from fossil fuels, present a vital opportunity for further growth and enhancement of renewable fuels on a worldwide scale.[26] The Biden administration has established a new objective to produce 3 billion gallons of SAF by 2030.[27]

Understanding the overall benefits of SAFs involves recognizing the various emission-generating processes throughout SAF's life cycle. Emissions occur during combustion in

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[21] **Sustainable Aviation Fuel | AFDC**

[22] **Clean skies for tomorrow: Delivering on the global power-to-liquid ambition | McKinsey & Company**

[23] **SAF Deployment | IATA**

[24] **Sustainable Aviation Fuel: Agencies Should Track Progress Toward Ambitious Federal Goals [Reissued with Revisions May 17, 2023] | GAO**

[25] **IATA announces estimates for SAF production | Times Aerospace**

[26] **COP28 closes with "historic" pledge to transition away from fossil fuels | Engineering and Technology**

[27] **FACT SHEET: Biden Administration Advances the Future of Sustainable Fuels in American Aviation | The White House**

aircraft engines but are partially neutralized by the carbon captured during feedstock growth or collection. For SAFs derived from crops, this balance includes carbon absorption by the crops. However, SAF production also generates emissions from feedstock processing, transportation, and distribution, influenced by energy use and potential land use changes. For SAFs to provide net environmental and climate benefits, their life-cycle emissions must be lower than those from conventional jet fuel.

The ICAO uses the Total Life Cycle Emissions Factor (LSf) within its Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) model to assess the potential savings of different SAF technologies. This factor aggregates emissions across the entire fuel life cycle into a metric, expressed as grams of CO_2 equivalent per megajoule (g CO_2e/MJ).[28] It is influenced by factors such as the type of feedstock, energy source, and production process; the choice of the latter for a specific feedstock is significant. According to ICAO's documentation, when agricultural residues are processed using the Fischer-Tropsch method, the LSf is 7.7 gCO_2e/MJ. In contrast, processing the same feedstock via the alcohol-to-jet technology yields a significantly higher LSf of 29.3 gCO_2e/MJ. Moreover, the LSf varies depending on the feedstock, even within the same production technology. For example, SAF from corn grain in the United States through the alcohol-to-jet process exhibits a much higher LSf of 77.9 gCO_2e/MJ compared to 29.3 gCO_2e/MJ from agricultural residues. The life-cycle emissions of different feedstocks depend on factors such as cultivation methods, land use, biodiversity impact, and water resource use.

The differences in life-cycle emissions across feedstocks suggest that **not all are sustainable**. For instance, palm oil—a cheap vegetable oil used as feedstock in HEFA technology—is criticized due to the deforestation and habitat destruction associated with its cultivation (Ngan et al., 2022). Many airlines have decided against bio-jet fuel made from palm oil due to these sustainability challenges (Dyk and Saddler 2021). Although attention has shifted away from palm oil, similar issues affect other crop-based feedstocks. The central question is whether existing agricultural land can meet the increasing demands of the global population for both food and fuel. If not, more will be transformed for crop production, leading to indirect land use change (ILUC). Additionally, the use of edible crops as feedstock introduces further complications. For example, corn used for ethanol in ATJ technology may conflict with the food supply and raise food prices.[29]

These sustainability challenges necessitate carefully selecting feedstocks and production processes that minimize environmental impacts while fulfilling the demand for cleaner aviation fuels. The **accurate assessment** of these factors is crucial yet complicated by a lack of scientific consensus, stemming from the variability in models and estimation methods for assessing life-cycle emissions. For instance, the methodologies employed by CORSIA differ from the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model from the Argonne National

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[28] **CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels | ICAO**

[29] **The Case Against More Ethanol: It's Simply Bad for Environment | Yale Environment 360**

Laboratory differ, particularly for ILUC, which sometimes leads to conflicting evaluations of the sustainability and emissions savings of different SAF options.[30] This highlights the need for further research to reconcile these differences and provide clearer guidance for the development and selection of SAFs.

The **insufficient availability of necessary feedstock** for SAF production poses another challenge. The Waypoint 2060 report projects a need for 330–445 million tonnes of SAF, alongside other technological and operational advancements, for the aviation industry to reach net-zero carbon emissions by 2050 (ATAG 2021). However, whether the feedstock will be sufficient to meet this demand is unclear. Although a World Economic Forum (WEF 2021) report suggests that, globally, enough biogenic feedstocks exist to produce about 500 million tonnes of SAF by 2030, the reality of availability is more complex.

HEFA feedstocks, such as waste fats, oils, and greases, are limited due to their reliance on waste products, which are finite and depend on the scale of other human activities that produce these wastes. While the production of agricultural feedstocks might theoretically be increased, there is **intense competition from other sectors**, notably on-road transportation, which utilizes the same feedstocks and refinery infrastructure. This competition is evident from fuel retailers' opposition to the SAF tax credit proposed in the IRA.[31] Another report by ICF, a global consulting and technology services company, considers the potential competition for feedstocks and predicts that bio-based feedstock for SAF will only meet 50 percent of the demand required to hit the International Air Transport Association's 2050 net-zero carbon target (Blanshard et al. 2021).[32]

PtL technology can effectively address raw material shortages by harnessing widely available water and CO_2. However, the costs of renewable energy and CO_2 sourcing, taken together with the early-stage and energy-intensive nature of the production process, make PtL very expensive. In 2020, the cost of producing SAF through PtL was estimated to range from 3 to 9 times the historical average cost of fossil fuel.[33] Moreover, its environmental impact requires a nuanced examination of CO_2 source selection. Options for CO_2 acquisition include capture from industrial emissions—like cement manufacturing and waste incineration—or extraction from the atmosphere via Direct Air Capture (DAC). Using CO_2 from industrial activities could merely cycle carbon emissions back into the atmosphere upon fuel combustion, potentially increasing the overall carbon footprint. Conversely, DAC could theoretically lower atmospheric CO_2 but is less efficient and considerably more expensive. In 2019, DAC expenses were estimated at $125–350, in stark contrast to industrial capture costs, which ranged from $15-25/ton for high-concentration CO_2 streams to $40–120/ton for those less concentrated.[34]

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[30] CORSIA v. GREET for SAF: What to Do, What to Do | Transport Energy Strategies

[31] US fuel retailers rail against green aviation fuel tax credit | Reuters

[32] Bio-based feedstocks will likely only be able to provide half of SAF demand by 2050, finds ICF study | GreenAir

[33] Climate-Tech to Watch: Sustainable Aviation Fuel | ITIF

[34] Is carbon capture too expensive? | IEA

The concern of **high production costs** also extends to SAFs produced through other technologies; the scarcity of sustainable feedstocks and lack of mature production processes often result in increased production expenses. The high cost is crucial considering that fuel is a substantial component (20–30 percent) of the operating costs for airlines (IATA 2019). The stark contrast in fuel prices is evident; in 2020, the cost of producing SAF from HEFA was about 2 to 3 times the historical average cost of fossil fuel.[35] This price gap limits the demand for SAF and undermines the capacity of SAF refineries.

The high production cost of SAF necessitates **substantial financial backing**, which is challenged by uncertainties in technological development, feedstock limitations, regulatory unpredictability, and prolonged paths to profitability. HEFA, though technologically advanced, grapples with feedstock scalability. Newer SAF production methods such as ATJ, FT, and PtL are still in the early stages of development, presenting market risks. The heterogeneous quality of feedstocks used in biofuel technologies such as HEFA, ATJ and FT intensifies the risks as variations in the quality of feedstock can affect efficiency, cost, and compliance with sustainability metrics. Against this backdrop, the choice to utilize feedstocks and technologies to produce renewable diesel for ground transportation, rather than SAF, emerges as more financially viable due to its market readiness, compatibility with existing transportation fuel infrastructure, and the presence of supportive regulatory frameworks. Government incentives like subsidies, loan guarantees, and grants are essential for advancing SAF technologies to a point where they can draw private financial support. Without such interventions, SAF's feasibility and market competitiveness remains uncertain.

For distribution, SAF must be blended with conventional jet fuel before use. The integration method depends on whether SAF is a standalone product or coprocessed with jet fuel.[36] Coprocessing involves processing renewable feedstocks alongside crude oil in existing petroleum refineries, resulting in a blend that can be seamlessly integrated into the existing supply chain. On the other hand, standalone production requires **additional infrastructure**, such as blending facilities, storage tanks, and transportation logistics to move the neat SAF from the production site to the blending site.

Finally, SAF presents a significant opportunity to reduce air pollution due to its **low content of aromatic hydrocarbons**, which are compounds in traditional jet fuels that produce soot and PM when burned. However, this also poses a challenge, as aromatics play a critical role in preserving the integrity of seals within aircraft engines and fuel systems, averting seal failures, fuel leaks, and equipment malfunctions.[37] Without aromatics, seals may shrink, leading to fire safety hazards, expensive repairs, and grounding, especially in older aircraft engines and fueling infrastructure. Jet fuel standards mandate a minimum aromatic content of 8 percent to uphold seal integrity. Leveraging SAF's full health benefits requires new technologies and materials for seals that work with low-aromatic SAFs.

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[35] **Annual Technology Baseline - Jet Fuel | NREL**

[36] **Sustainable Aviation Fuel | US Department of Energy**

[37] **Sustainable aviation fuels are not all the same and regular commercial use of 100% SAF is more complex | GreenAir**

3.2. Hydrogen Aircraft

Two main methods exist for using hydrogen in aircraft. The first uses fuel cells to turn hydrogen into electricity, powering electric motors. The second burns hydrogen in internal combustion engines to generate power, as in traditional engines. Hydrogen fuel-cell aircraft substantially reduce emissions, producing primarily water vapor without NO_x or PM. Although hydrogen combustion engines also reduce pollutants compared to conventional jet fuel, they might emit some NO_x at high temperatures. However, both methods successfully eliminate CO_2, SO_2, and PM. Research estimates that hydrogen combustion and fuel-cell technologies could reduce climate impact in flight by 50–75 percent and 75-90 percent, respectively, compared to kerosene-powered aircraft.[38]

The largest hydrogen fuel-cell aircraft to have flown in the past years is the 40-passenger regional airliner by Universal Hydrogen.[39] Another company, ZeroAvia is developing a 2–5MW modular hydrogen-electric powertrain for regional turboprops that can carry up to 80 passengers up to 1,000 NM, aiming for completion by 2027.[40] The low passenger capacity and range of hydrogen compared to conventional jet-fuel aircraft is due to hydrogen's lower volumetric energy density compared to liquid fuels such as kerosene. It has two main storage methods: liquid (LH_2) at -253°C, which saves space but requires advanced cryogenic technology, and compressed gas, which is less space-efficient and requires high-pressure systems. At standard conditions, about 3,000 liters of hydrogen gas are needed to match the energy of one liter of kerosene. Compressing it to 700 bars reduces this volume to about six liters, and LH_2 brings it down to four liters. Liquid hydrogen storage is more promising for aviation due to space and weight constraints. ICCT estimated that, by 2035, LH_2-powered narrow-body aircraft could transport 165 passengers up to 3,400 km and LH_2-powered turboprop aircraft could transport 70 passengers up to 1,400 km. Together, they could service about one-third (31 to 38 percent) of all passenger aviation traffic, as measured by revenue passenger kilometers (Mukhopadhaya and Rutherford 2022). According to Graver et al. (2019), about one-third of aviation's CO_2 emissions in 2018 originated from flights shorter than 1,500 km. Based on projections by Mukhopadhaya and Rutherford (2022), hydrogen technology could be developed to a point where it could substitute for at least these 33 percent of emissions.

In contrast, the high volume and mass make hydrogen gas impractical for most aviation purposes. Some key innovations in hydrogen storage are focusing on lighter tanks using carbon composite materials and increasing the density of LH_2 with gelled or slush hydrogen. Companies such as ZeroAvia are also exploring cryocompressed hydrogen, which blends cryogenic cooling and compression, leading to higher storage densities, reduced boil-off, and faster refueling.[41]

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[38] **Hydrogen-powered aviation | Clean Hydrogen Partnership**

[39] **Universal Hydrogen Successfully Completes First Flight of Hydrogen Regional Airliner | Universal Hydrogen**

[40] **ZA2000 | ZeroAvia**

[41] **Cryo-compressed hydrogen: A 40% aircraft range boost over liquid H_2 | New Atlas**

Although hydrogen-powered aircraft are not yet used in commercial aviation, several reports draw attention to their potential. Heathrow Airport's report suggested that hydrogen planes may start serving the UK's short-haul and regional routes commercially by the second half of the 2020s, with the potential for a complete transition of the regional fleet by 2040.[42] Additionally, the Hamburg and Rotterdam airports are collaborating to launch hydrogen flights between the cities by 2026.[43] A study by Transport and Environment (T&E) indicates that, with supportive policies and incentives, hydrogen planes in Europe could become economically viable and potentially more affordable than fossil fuel–powered planes by 2035.[44]

However, transitioning regional flights to hydrogen aircraft would require addressing challenges. First and foremost is **safety**. The 1937 Hindenburg disaster, where a hydrogen-filled German airship caught fire and crashed, is well known for underscoring the historical risks. Yet, when handled responsibly, hydrogen is safer than conventional fuels in a couple of ways: it is nontoxic and does not pose the same environmental or health risks in a leak or spill. It is much lighter than air and gasoline vapor, which enables it to disperse quickly and reduces ground-level ignition risks. It requires a higher concentration of oxygen to explode compared to gasoline, making it less prone to explosions in typical environments.[45] Technological advancements and strict regulations have significantly improved safety. Modern materials, enhanced engineering practices, and robust safety protocols have been developed to mitigate risks, making hydrogen a viable option as an energy carrier (Bruce et al. 2020). Studies indicate that it could be cleaner and safer than jet fuels, improving performance, reducing operating costs, and offering better availability and economic impacts (Brewer 2017; Yılmaz et al. 2012). However, the **public perception of hydrogen safety is mixed**, influenced in part by history. A social media survey revealed that only about 50 percent of the respondents consider it generally safe.[46] Moreover, further research is necessary to learn the proper management of hydrogen in aviation.

Another significant hurdle is **lengthy and complex certification processes**, varying by country and overseen by authorities such as the FAA and European Union Aviation Safety Agency. The complexity is due to their distinct operational and safety requirements, differing significantly from traditional engines. Manufacturers must meet uncertain FAA regulations and design requirements while improving the technology to satisfy safety and performance standards.

The widespread adoption of hydrogen aircraft in commercial aviation also necessitates significant **investment in airport infrastructure**, such as specialized tanks for handling and storing LH_2 with strict temperature control conditions and trucks with insulated

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[42] **Project NAPKIN | Heathrow Airport**

[43] **Hamburg and Rotterdam announce hydrogen flight corridor collaboration, setting sights on 2026 first flight | Hamburg Airport**

[44] **Running a hydrogen plane could be cheaper than traditional aircraft by 2035 | Transport & Environment**

[45] **Hydrogen Safety: Let's Clear the Air | NRDC**

[46] **Hydrogen power is safe and here to stay | World Economic Forum**

fuel tanks to facilitate aircraft refueling. Upgrading airport fuel delivery systems and providing specialized safety training for staff are also necessary. These changes are expected to **raise operational costs**. Moreover, **logistical challenges** can arise. For instance, unlike with jet-fueled aircraft, it is likely not feasible to refuel while passengers are on board due to safety concerns. This limitation could increase flight turnaround times, indirectly adding to airline operational costs.

Additional challenges are related to production and delivery. Hydrogen fuel can be produced through various methods, each with a different environmental impact, often categorized by a color system. Green hydrogen, produced through the electrolysis of water using renewable energy sources (like in PtL technology), is the most environmentally friendly option. Blue and gray are from natural gas with and without carbon capture technologies, respectively. The environmental benefits of hydrogen as a fuel source are closely tied to how green the production method is, with greener methods offering more benefits. Gray hydrogen production leads to **environmental justice issues**, as communities near oil refineries, main sites of hydrogen production, suffer from higher pollution levels.[47]

Irrespective of the production method, **the cost of producing and delivering hydrogen** is a significant challenge, stemming from the complexities and required safety measures. Building hydrogen pipelines, for example, is costlier than for other fuels due to the need for special materials to prevent hydrogen permeation and resist embrittlement. Demir and Dincer (2018) indicated that the levelized cost of delivering hydrogen is $2.73–8.02 per kg. In comparison, the price of jet A fuel in 2022 was around $0.82 per kg.[48]

Production costs also vary depending on the type of hydrogen, with gray costing $0.98–2.93 per kg, blue $1.8–4.7 per kg, and green $4.5–12 per kg in 2023.[49] Only about 1 percent of global production is green.[50] Most US production is gray.[51] The **higher cost of producing green hydrogen** makes the transition to environmentally friendly production financially challenging. However, new incentives under the IRA are promoting cleaner production methods.[52]

Scaling hydrogen aviation would also necessitate **collaboration among a range of stakeholders**. Airlines would have to work with airport authorities to address their unique operational needs for fueling infrastructure. Airports, in turn, would need to collaborate closely with fuel suppliers to ensure a reliable and sufficient supply, with a focus on green hydrogen. Engaging with environmental advocacy groups and the local

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[47] **Reclaiming Hydrogen for a Renewable Future: Distinguishing Oil & Gas Industry Spin from Zero-Emission Solutions | Earth Justice**

[48] **How much does jet fuel cost: The price of jet fuel and fueling an aircraft | FDF**

[49] **Green Hydrogen to Undercut Gray Sibling by End of Decade | BloombergNEF**

[50] **Hydrogen – Overview | IRENA**

[51] **Hydrogen's present and future in the US energy sector | Shearman & Sterling**

[52] **Incentives for Clean Hydrogen Production in the Inflation Reduction Act | RFF**

community to mitigate any environmental and social impacts would be crucial, as would coordinating with international aviation organizations to facilitate global flight operations.

Finally, using hydrogen as a fuel in aircraft will still result in water vapor emissions, potentially **increasing the formation of contrail clouds** (Rap et al. 2023). Research aimed at mitigating contrail formation can further enhance the environmental benefits of hydrogen aircraft.

3.3. Electric Aircraft

Electric aircraft promise several benefits over jet-fueled aircraft: they produce zero emissions in flight; using renewable sources can further reduce their carbon footprint. They also produce significantly lower noise (Schäfer et al. 2019) and may require less maintenance because electric motors are simpler than combustion engines. However, this technology also faces several challenges.

Electric aircraft have **significant limitations in passenger capacity and range** compared to jet-fueled and hydrogen aircraft. The Alice, developed by Israeli start-up Eviation, seats nine and targets a maximum range of approximately 500 miles.[53] However, companies are developing larger electric aircraft. For example, Heart Aerospace is working on the ES-19, a 19-passenger plane with a range of 250 miles, and the ES-30, a 30-seat hybrid airliner capable of flying up to 500 miles.[54, 55] Wright Electric is focusing on the Wright Spirit, a retrofit of the 100-passenger Bae 146 for electric operation, targeting one-hour flights.[56] In comparison, the Boeing 737-800, a commonly used jet-fueled plane, can accommodate 189 passengers and has a range of up to 3,600 miles, underscoring the significant gap in capacity and range.

That limited passenger capacity and range is mainly because batteries have a lower energy density than fossil fuels or hydrogen. Adding batteries to these planes significantly affects their weight and size; the best available batteries can increase weight by about one-third. Moreover, unlike other types of aircraft, electric planes cannot lighten their load during flight, as they must always carry the full weight of their batteries. Batteries also occupy considerable space and contribute to increased drag—the air resistance that reduces energy efficiency. Additionally, the need for reserve capacity, such as enough power to circle an airport for 30 minutes or reach an alternative airport 100 km away in emergencies, can significantly limit the practical range.

Battery technology, with its low energy density, limits electric aircraft mainly to very short flights. A report by ICCT examined electric aircraft with 9, 19, and 90 seats, considering

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[53] **Alice, the first all-electric passenger airplane, takes flight | CNN**

[54] **Heart Aerospace partners with Aernnova to design and develop the structure for the ES-19 Electric Airplane | Heart Aerospace**

[55] **Heart Aerospace unveils new airplane design, confirms Air Canada and Saab as new shareholders | Heart Aerospace**

[56] **The Wright Spirit | Wright**

different battery capacities and proportion of aircraft's weight that is composed of batteries. With today's batteries (250 Wh/kg), a nine-passenger electric plane could only achieve an operational cruise range of 140 km and replace a tiny fraction (0.03 percent) of total flight distance covered by all planes and 4 percent of all flight departures. If battery technology advances to 500 Wh/kg, larger planes could fly up to 280 km, possibly replacing larger turboprop planes, but this would still only affect 0.7 percent of global flight distance and 9 percent of departures. Overall, this would only minimally reduce jet fuel use. By 2050, if battery technology improves and electric planes are used wherever possible, it could cut aviation's carbon emissions by 3.7 million tonnes yearly, just 0.2 percent of the projected annual emissions of 1,840 Mt of CO_2e from passenger aviation in that year. Consequently, alternative fuels, such as SAF and green hydrogen, which have higher energy densities, are more suited for longer flights, provided they are economically feasible (ICCT, 2022). While the overall impact of electric aircraft on climate change may be limited, they could replace a nontrivial proportion of total flight departures and notably improve air quality around airports, underscoring their value in environmental improvement strategies. Moreover, if electric aircraft partly or fully replace small piston engine aircraft—a significant source of lead emissions in the US, they can substantially reduce lead levels in the air.

An additional challenge is developing **adequate charging infrastructure**. For example, the Alice can fly for 1 hour after 30 minutes of charging, so it requires intraday recharging for multiple daily flights, highlighting the need for high-speed charging solutions.[57] The advancement in battery range will raise a new challenge applicable to all electrification-based decarbonization solutions, which is developing an advanced, scalable, and adaptable **grid infrastructure**. Lohawala and Spiller (2023), although focused on medium heavy-duty electric trucks, underscore the need of significant power grid enhancements for greater capacity and reliability, which is equally crucial for electric aircraft. Additionally, to fully realize the environmental advantages, electricity would need to come from renewable sources. Using electric aircraft in commercial aviation will require airports to integrate distributed generation systems, on-site energy storage, and smart grid technologies to manage peak energy demands and ensure a steady power supply.

Although battery technology is unlikely to support long-range flights, recent advances in it and other supporting technologies have made short-range urban and intracity flights increasingly feasible. For instance, Joby Aviation has conducted thousands of test flights with its five-seat piloted electric vertical takeoff and landing (eVTOL) aircraft and plans to begin commercial services in 2025. Airbus SE, Archer Aviation, and Beta Technologies are among the many other innovators in this emerging field.[58] These eVTOL aircraft, commonly known as "air taxis," are expected to initially serve routes such as city center to airport connections. Distinct from current aviation emissions, Sripad and Viswanathan (2021) suggest that eVTOLs could significantly reduce total transportation emissions, potentially outperforming electric cars for short trips. This market presents significant opportunity, but many challenges exist

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[57] **Alice, the first all-electric passenger airplane, prepares to fly | CNN**

[58] **Top 13 eVTOL Aircraft Companies in the World | imarc**

to realizing this technology, including substantial investment requirements, evolving regulatory landscape, and proving market viability.

Finally, like hydrogen technologies, electric aircraft face **lengthy and complex certification processes**.[59] The FAA notes that certifying new eVTOL aircraft can take 5–9 years, so companies often need to spend several years working toward market entry without generating revenue.[60]

3.4. Hybrid-Electric Aircraft

Another potential solution for carbon emission reduction is hybrid-electric aircraft, which use several energy sources in flight, either in tandem or alternately, and can lead to better energy management and reduced fuel consumption.[61] Wroblewski and Ansell (2019) found that a propulsion system with a combination of electric power and traditional fuel could reduce the life-cycle CO_2 emissions of a commercial aircraft, such as the Boeing 737-700, by approximately 49.6 percent without compromising its flight range, suggesting that hybrid-electric aircraft could be a viable and more environmentally friendly option for commercial aviation. Prashanth et al. (2021) examined selective catalytic reduction systems in aircraft engines, which can cut NO_x emissions by roughly 95 percent and prevent approximately 92 percent of early deaths linked to aviation air pollution each year. The study highlights that these systems are especially compatible with emerging hybrid or turbo-electric designs.

Hybrid electric aircraft overcome some limitations of electric aircraft, enhancing range and capacity with dual propulsion. Despite this, they require airport charging or refueling infrastructure and must undergo rigorous, evolving certification processes, echoing the hurdles faced by fully electric and hydrogen models. Recent years witnessed several demonstrations of hybrid-electric aviation, highlighting the ongoing advancements in the field. Notable examples from 2023 include the successful test flights of Ampaire's Electric EEL, Daher, Safran, and Airbus's EcoPulse.[62, 63]

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[59] **What Challenges Still Exist for Certifying Electric Aircraft | Avionics International**

[60] **Building Next-Gen Aircraft Requires Agility | Spirit Aerosystems**

[61] **Hybrid and electric flight | Airbus**

[62] **Ampaire Makes Aviation History with First Hybrid Electric Flight into Silicon Valley | PR Newswire**

[63] **The World of Air Transport in 2019 | ICAO**

4. Challenge 2: Voluntary Changes in Passenger Behavior

Focusing on consumer choices is as crucial as technological innovation to effectively reduce aviation emissions, given the consistently high and increasing demand for air travel. In 2019, airlines worldwide carried about 4.5 billion passengers, expected to grow to about 10.0 billion by 2040.[64] The primary challenge lies in persuading them to opt for more sustainable choices, such as ground transportation (such as trains and buses) whenever possible, contributing to carbon offset programs, and choosing greener flights.

Despite greener alternatives, many passengers favor air travel for its speed and convenience. For lengthy or international journeys, it offers the obvious advantage of covering vast distances quickly. For remote areas, such as Alaska, it may be the only viable option. However, **people often prefer flying even for shorter distances** due to more affordable prices from budget airlines and the lack of robust train and bus infrastructure. Getting people to switch voluntarily to trains and buses for short-distance travel requires enhancing these systems, offering competitive pricing, improving amenities to make them more appealing, and increasing public awareness about their benefits. Yet, such infrastructure improvements can be costly and challenging. California's 2008 high-speed rail project illustrates these difficulties. Despite 14 years of effort and approximately $5 billion spent, the project remains unfulfilled due to funding shortages, political opposition, land acquisition issues, and regulatory hurdles.[65]

Switching to a greener alternative is not always feasible. In such cases, individuals can purchase voluntary carbon offsets (VCOs) to compensate for their GHG emissions. Offsets were introduced in the Kyoto Protocol in 1997 to fund projects that reduce, avoid, or sequester emissions, such as renewable energy, reforestation, or energy efficiency projects. Air passengers can consider purchasing them when it is more cost-effective than directly avoiding emissions by not taking a flight, and this can theoretically achieve an equivalent GHG impact.

Yet, the **effectiveness of carbon offsets is questionable**. It is often hard to prove that the emission reductions directly result from the offset project and would not have happened otherwise. For example, some renewable energy projects might be economically feasible without offset funding. Moreover, projects such as forestry face the issue of permanence, as trees can release stored carbon if cut down or destroyed. The risk of unintended emissions displacement also arises—if one area is protected, emissions might shift elsewhere. Last, offsets can worsen existing inequalities if they negatively affect local communities. Due to these issues, even the passengers willing to offset their emissions may be skeptical about the real impact. Ensuring transparency, implementing better regulations, and providing assurance are crucial to building trust and encouraging participation.

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[64] **The World of Air Transport in 2019 | ICAO**

[65] **Train to nowhere: can California's high-speed rail project ever get back on track? | The Guardian**

Another key challenge is **enabling passengers to select flights with lower emissions**. Historically, flight comparison websites did not provide information on flight emissions, but platforms such as Skyscanner, Google, and Kayak have recently started doing so. However, inconsistencies in the information provided arose from differing methodologies: Google Flights used the Travel Impact Model,[66] Kayak's Atmosfair model,[67] and Trip.com's CHOOOSE model.[68] Although all models calculate emissions per passenger based on flight distance, aircraft type, and service class, their varying methods could result in different emissions rankings for the same flights, leading to confusion among travelers about the actual environmental impact. A 2021 article by ICCT highlighted significant discrepancies in CO_2 emissions data for the same flight across different platforms.[69] Table 1 shows a table from this article with the airlines' rankings based on their emissions per passenger for a roundtrip flight from Los Angeles (LAX) to New York (JFK), demonstrating that Google Flights' emissions estimates were 17–41 percent lower than the combined average estimates of Lite Flights and Kayak, varying based on the specific itinerary.

Table 1. Airlines' Rankings by Emissions per Passenger on an LAX–JFK Roundtrip, in Ascending Order

Lowest emission	Google Flights	Lite Flights	Kayak.com	Skyscanner
1	American (922 kg)	JetBlue (1288 kg)	JetBlue (1247 kg)	Alaska (20% less)
2	Alaska (948 kg)	American (1598 kg)	American (1517 kg)	JetBlue (5% less)
3	Delta (980 kg)	Alaska (1598 kg)	Alaska (1613 kg)	
4	JetBlue (1054 kg)	United (1850 kg)	Delta (1712 kg)	
5	United (1181 kg)	Delta (1850 kg)	United (2000 kg)	

Data source: ICCT

It is not clear if these websites still use different models, but what is clear is the need for a uniform, comprehensive calculation method. It should incorporate factors such as airlines' sustainable practices and SAF usage, ensuring more accurate and consistent environmental impact information for consumers. Furthermore, a pressing need exists to motivate more websites to include emission data. Initiatives such as the Travelyst coalition are working toward this aim.[70] It seeks to promote sustainable travel by standardizing emissions reporting across platforms, which would greatly assist travelers in making environmentally conscious choices.

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[66] **Travel impact models 1.8.0 | github**

[67] **A way to search for flights with less CO_2 emissions | Kayak**

[68] **Offsetting your flight's carbon emissions with Trip.com | Trip.com**

[69] **Scanning the sky for lite flights | ICCT**

[70] See Travalyst website: **https://travalyst.org/**

5. Challenge 3: Operations and Management

Flight operational optimization strategies, including flight planning, optimizing flight's ground operations, fuel-efficient flying, and advanced air traffic management (ATM), can also be implemented to reduce aviation emissions. Flight planning can involve strategic flight scheduling, route selection to minimize fuel consumption, and gate assignments aimed at reducing aircraft taxi times (Jalalian et al., 2019). During ground operations, practices such as single-engine taxiing and engine-out taxi can lower fuel usage during taxiing.[71, 72] Fuel-efficient flying techniques, including optimized ascent and descent paths and speed management, can help reduce aerodynamic resistance and fuel consumption.[73] ATM enhancements can further support emission reductions through advanced navigation systems enabling more direct routes, weather-adjusted flight paths, and streamlined air traffic flows.[74]

Yet, these optimizations often involve balancing improvements in air quality, CO_2 emission reductions, and passenger experience. Research shows that the **efforts to decrease CO_2 emissions can inadvertently raise other emissions**. Using a model that simulates atmospheric chemistry, Ashok et al. (2014) illustrate that trade-offs happen 2–18 percent of the year for $PM_{2.5}$ and 5–60 percent for O_3, influenced by factors such as airport location, engine type, and thrust setting, and can be significant: for each kilogram of increased fuel burned at a constant thrust during these periods, the reduction in exposure to $PM_{2.5}$ and O_3 can be 6–13 and 32–1,060 percent, respectively, compared to the annual average per kilogram of fuel burned. Similarly, Skowron et al. (2021) highlight a technological tradeoff between NO_x and CO_2; reducing NO_x emissions might result in a fuel penalty that can negate climate benefits. These findings suggest the need for joint optimization of multiple objectives for the lowest environmental impact.

Additionally, **CO_2 emissions and passenger experience must be balanced**; for example, efforts to minimize CO_2 emissions by flying at slower speeds can result in longer flights, potentially affecting passenger experience (Jalalian et al. 2019). Faster flight speeds create more aerodynamic resistance, necessitating more fuel to maintain speed (Sadraey 2009).

Airports and airlines can also reduce their non-flight operational emissions through strategies such transitioning to electrified ground support equipment (GSE) like baggage tugs and belt loaders. For instance, Delta Air Lines is nearing 100 percent electrification of its ground support equipment at Salt Lake City and Boston Logan

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[71] **Why Qatar Airways Is Asking Its Pilots to Taxi on One Engine | Simply Flying**

[72] **Iberia Airlines Taxiing Program to Reduce Emissions at ORD | Aviation Pros**

[73] **What you need to know about Continuous Descent Approach | OpenAirlines**

[74] **Single European Sky: for a more sustainable and resilient air traffic management | European Commission**

International Airports.[75] Additionally, airports can shift to electric shuttle buses, and promote or require EVs for rental car services. Beyond transportation, improving the energy efficiency of airport buildings through upgraded lighting and heating, ventilation, and air conditioning systems can offer further opportunities to lessen environmental impacts. Though these measures may not significantly lower aviation's global climate effects, they can improve local air quality.

However, adopting such initiatives can significantly increase airports' peak energy demands, sometimes even doubling them. This surge necessitates a considerable expansion of grid capacity, a process that may extend over several years due to the complexities involved in utility-scale grid enhancements. Airports like Pittsburgh International Airport are leading the way by adopting solar panels and developing microgrids, not only to meet operational needs but also to provide clean, resilient energy sources. It became the first airport to be entirely powered by natural gas and solar energy through a microgrid in 2021.[76]

However, implementing sustainability in airports goes beyond integrating clean energy. It includes transforming operations, educating and training employees, and securing funds, all of which could greatly benefit from policy support.

6. Challenge 4: Unclear National Responsibilities

In 2018, international flights represented only 33 percent of total flights but 60 percent of global aviation emissions. (Graver et al., 2019). The effort to mitigate the environmental impact of international aviation is complex, hindered by the **absence of clear responsibility among nations for the emissions generated**. This challenge arises because emissions occur predominantly in international airspace, complicating the process of attributing them to specific nations.

Under the UNFCCC, emissions from international air travel, categorized as "bunker fuels" alongside international shipping emissions, were not included in the individual countries' emissions totals. These emissions were to be reported separately from the national totals and, during development of the 1997 Kyoto Protocol, countries agreed to address emissions from these bunkers through the ICAO negotiations and not through the UNFCCC. Whether causal or not, this separation allowed Annex I Parties to increase emissions from these sectors without affecting their emission reduction commitments. For example, the bunker fuel emissions from US aviation rose from 39 $MtCO_2e$ in 1990 to 79 $MtCO_2e$ in 2019 (Figure 2) based on the UNFCCC database on GHG Inventory,[77] indicating a growing share in the total transportation GHG emissions.

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[75] **Tugs, tractors and belt loaders nearly all electric at two Delta hubs | Delta**

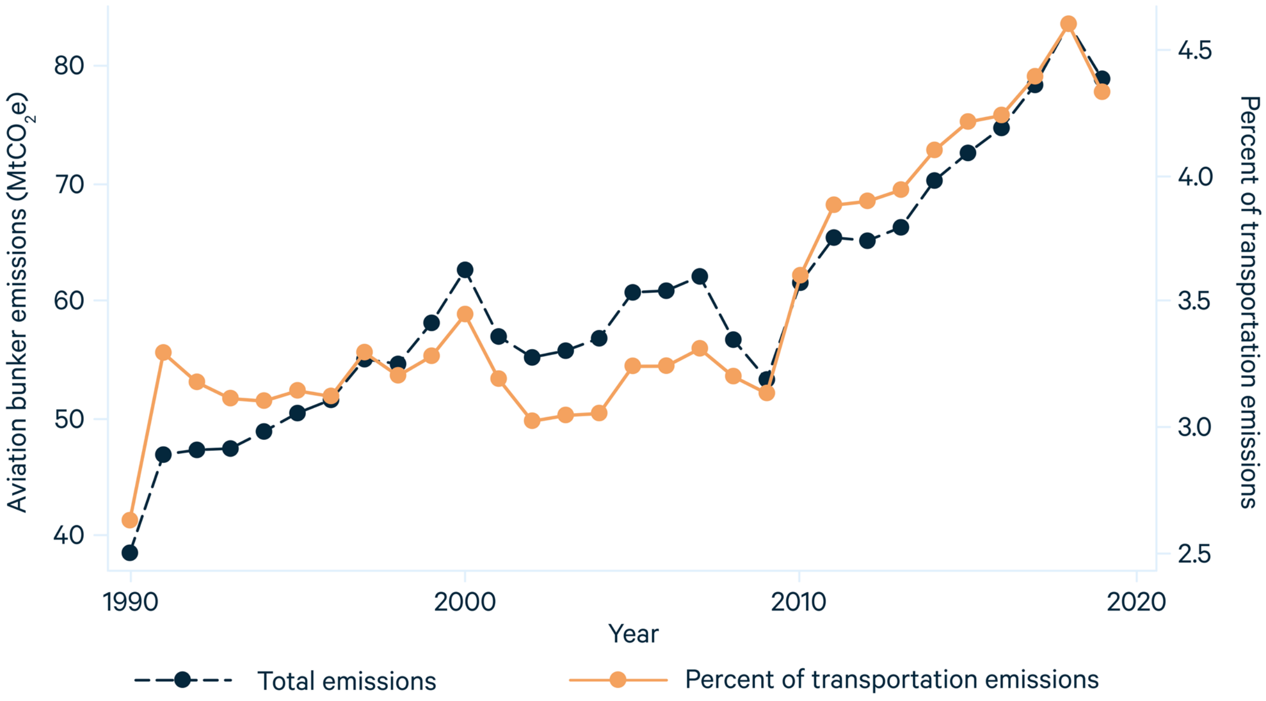
[76] **Pittsburgh International Airport Goes Live with First-of-Its-Kind Microgrid Powering Entire Facility with Natural Gas and Solar Energy | ACAA**

[77] **Greenhouse Gas Inventory Data - Time Series - Annex I | United Nations**

More recently, that separation has turned to ambiguity. The lack of specificity in the 2015 Paris Agreement has resulted in nationally determined contributions (NDCs) submitted by parties primarily focusing on domestic emissions, leaving emissions from international transport largely unaddressed.[78]

While there was little progress on international emissions for nearly two decades, ICAO introduced CORSIA in 2016, aiming to stabilize CO_2 emissions from international flights. This represents a significant global initiative directed at international aviation. However, as CORSIA focuses on the responsibilities of airlines rather than countries, countries still need to take responsibility. Integrating these emissions into overall climate policies requires more than airline involvement. For example, developing a sustainable supply chain for SAF necessitates collaborative efforts beyond the aviation industry, involving fuel producers, regulatory bodies, and various economic sectors, which underscores the need for countries to actively support such collaborations through well-crafted policies and regulatory frameworks.

Figure 2. Bunker Fuel Emission from US Aviation



Source: Authors' own calculations based on UNFCCC database on GHG inventory.

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[78] **The Paris Agreement and Implications for Reducing Aviation Emissions | WWF**

7. What Different Stakeholders Can Do

Understanding the roles and capabilities of industry stakeholders in decarbonizing aviation is key to meeting the 2050 net-zero goal. Table 2 examines the roles of aircraft manufacturers, maintenance, repair, and overhaul (MRO) providers, airlines, airports, passengers, SAF producers and suppliers, and air traffic controllers. We discuss policy in the next section.

Table 2. Roles and Actions of Stakeholders

Stakeholders and their roles	Actions	Examples
Aircraft Manufacturers and MRO Providers: Develop and produce aircraft; offer maintenance, repair, and overhaul (MRO) services for aircraft and their components.	Improve aircraft technology to improve fuel efficiency. Electrify ground transportation for MRO. Invest in emerging technologies, such as electric and hydrogen aircraft.	**Airbus** aims to create the world's first hydrogen zero-emission commercial aircraft by 2030. The company's focus includes three ZEROe concept aircraft, which are hybrid models that use hydrogen combustion in specially adapted gas turbine engines for propulsion. **Boeing** has enhanced its renewable energy use in manufacturing; invested heavily in technologies to cut fuel use, emissions, and noise; and increased its procurement of SAF for commercial activities.
Airlines: Operate the aircraft; make strategic decisions regarding fuel, fleet renewal, and operational efficiency.	Promote the purchase and use of SAF. Give air passengers loyalty-program rewards as incentives to offset CO_2 through SAF use. Accelerate fleet renewal to introduce more efficient aircraft. Display flight emissions information to air passengers.	Since 2019, European low-cost carrier **EasyJet** has provided free carbon offsetting for passengers. It operates a modern, fuel-efficient fleet, including Airbus Neo aircraft, which are on average 17% more fuel-efficient and reduce noise by 50% compared to older planes. **United** started showing consumers information on emissions in February 2023.
Airports: Provide infrastructure (e.g., fueling) and facilities (e.g., air traffic control centers).	Create infrastructure for charging electric aircraft and refueling hydrogen fuel. Optimize operations to minimize climate and air quality impacts (gate holding, reduced-thrust takeoffs, gate assignments, flight scheduling, aircraft-path assignment). Increase investments for building sustainable airports.	**Dulles International Airport** in Virginia plans to host the largest US airport clean energy project by 2026, including a 100 MW solar farm with 200,000 panels and 50 MW battery storage on 835 acres, powering 37,500 households. The **Hamburg and Rotterdam airports** are collaborating to launch hydrogen flights between the cities by 2026, focusing on infrastructure, renewable energy production, employee training, and smart technology development.

Stakeholders and their roles	Actions	Examples
Air Passengers: Influence airlines' practices and fuel choices through their choices and preferences.	Fly less, switch to trains and buses for domestic travel, choose greener flights, invest in carbon offsets, and pack lighter.	38% of National Geographic readers surveyed in a morning poll have either already paid or expressed a definite or probable willingness to pay an extra fee to compensate for carbon emissions generated by their air travel (National Geographic Staff 2022).
SAF Producers and Suppliers: Develop, refine, and scale up production of SAF from renewable feedstocks.	Set sustainable SAF production targets for their businesses, and develop strategies to achieve them. Replace traditional fossil fuel with SAF, or blend SAF with conventional jet fuel. Improve infrastructure for storing and delivering SAF.	**Neste** plans to expand its SAF production capacity to 1.5 million tons by early 2024 and is forging innovative partnerships to enhance the global accessibility of sustainable aviation fuel. **TotalEnergies** aims to manufacture 1.5 million tons of SAF annually by 2030, representing a 10% share of the global SAF market by that year.
Air Traffic Controllers: Manage and direct aircraft movements within airspace.	Improve operational and management efficiency in the air (e.g., air traffic control optimization, optimal cruise setting) through pilot training, contrail avoidance, and artificial intelligence.	The US FAA's concept for **Operations for an Info-Centric National Airspace System** is designed to be a dynamic framework. It capitalizes on innovative technologies to enhance service delivery to current users and enables the national system to rapidly adapt to new and changing types of operations.

8. Policy Solutions

Well-shaped policies can help reduce aviation GHG emissions while sustaining mobility for passengers and time-sensitive cargo and meeting future demand for air travel. In this section, we discuss some policy solutions.

8.1. Policies to Promote the Production and Usage of SAF

Policies that support SAF production, usage, and innovation are vital to tackle challenges such as high costs and limited supply to boost competitiveness with regular jet fuel. Such policies can include financial incentives, market-based measures, R&D investment, and mandates and taxes on fossil fuels.

8.1.1. Incentives

Financial incentives, as grants, tax credits, or other regulatory benefits, can help offset the high costs of SAF, fostering feedstock cultivation, infrastructure development, R&D, and use.

Recognizing the crucial role of SAF in reducing the aviation sector's climate footprint, several US federal agencies have taken active steps under the Sustainable Aviation Fuel Grand Challenge to promote its production and use. In 2021, the US Department of Energy's Loan Programs Office announced the availability of loan guarantees of up to $3 billion for commercial-scale SAF projects employing innovative technologies that can significantly lower GHG emissions, provided they meet certain criteria. The Department of Energy (DOE)'s Bioenergy Technologies Office announced funding of more than $61 million for biofuel research aimed at reducing transportation emissions, including research on lowering the cost of SAF pathways.[79]

In 2022, the US IRA also introduced multiple incentives to support SAF development. First, it allocated $297 million to the Department of Transportation (DOT) to fund competitive grants for projects related to producing, transporting, blending, or storing SAF or projects related to other low-emission aviation technologies.[80] In addition, it provided a two-phase tax credit scheme for SAF. Phase 1 provides a credit starting at $1.25 per gallon and potentially rising to $1.75 from 2023 to 2024 for fuels achieving a 50 percent or greater reduction in GHG emissions than conventional jet fuel.[81] Phase 2 initiates the Clean Fuel Production Credit (CFPC) from 2025 to 2027. It sets a baseline emissions factor for SAF and offers a $1.75 base credit, adjusted for inflation. To be eligible, SAF must have an emissions factor at or below 50 kg CO_2e/MMBtu and be produced in the United States at facilities adhering to prevailing wage and apprenticeship standards for the locality and profession. The value of CFPC is calculated by adjusting the fuel's emission rate against the 50 kg CO_2e/MMBtu baseline, dividing this by the baseline, and multiplying by the base credit.[82]

Some US states also have established incentives to promote the production and use of SAF. For instance, Washington State has enacted legislation that offers a per-gallon incentive for SAF that cuts life-cycle GHG emissions by at least 50 percent compared to conventional jet fuel. The incentive scales upward for every 1 percent reduction above the 50 percent threshold, maxing out at $2 per gallon. This incentive program is set to activate once a facility can produce a minimum of 20 million gallons annually.[83]

However, accurately measuring life-cycle emissions of SAF is challenging due to several factors, including the variability of feedstocks, complex supply chains, indirect land use changes, evolving technology, energy inputs for production, and allocation of by-product emissions. The industry and environmental groups have been divided over the best method for calculating the life-cycle GHG reductions in each gallon of

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[79] **US Department of Energy Announces $61 Million for Biofuels Research to Reduce Transportation Emissions | energy.gov**

[80] **IRA section 40007 – Sustainable Aviation Fuel Grant Program | Inflation Reduction Act Tracker**

[81] **IRA section 13203 – Sustainable Aviation Fuel Tax Credit | Inflation Reduction Act Tracker**

[82] **IRA section 13704 – Clean fuel production credit | Inflation Reduction Act Tracker**

[83] **New Washington Law Incentivizes Local Sustainable Aviation Fuel Production | Port of Seattle**

SAF. Environmentalists have favored the CORSIA model, highlighting its accuracy in accounting for land use changes and associated GHG spikes. Producers have advocated for the GREET model, claiming that it better accommodates low-emission farming techniques, such as strip-tilling and nitrogen fixation, and does not unjustly penalize farmers for land conversion. This debate highlights the inconsistency in emissions models and the need for an updated and accurate universal standard for measurement.[84]

8.1.2. Market-Based Measures

Market-based measures, such as carbon pricing, emissions trading systems, and offsetting requirements, create financial motivation for airlines to limit their climate footprint by adopting SAF and also indirectly promote developing more fuel-efficient aircraft by increasing demand.

One example is the EU Emissions Trading System (EU-ETS), a comprehensive cap-and-trade system designed to limit GHG emissions across various sectors, including power plants, industrial factories, and, as of 2012, the aviation sector. It sets a cap on the total volume of emissions allowed within these sectors. Within the cap, companies receive or buy tradable allowances, each granting the right to emit one tonne of CO_2 or an equivalent amount of other GHGs, such as nitrous oxide (N_2O) and perfluorocarbons (PFCs). Annually, the cap is lowered to reduce total emissions progressively, incentivizing entities to embrace environmentally friendly practices.

EU-ETS mandates airlines operating within Europe, regardless of their country of origin, to adhere to this system. Airlines are required to monitor, report, and verify their CO_2 emissions and must acquire enough allowances to cover them. Initially, EU-ETS aimed to cover all flights within, to, and from Europe. However, it aroused strong criticism and protest from the United States, China, and other countries due to its extraterritorial application, perceived violation of international aviation law, and economic impact on non-European airlines. As a result, its scope has been primarily limited to intra-European flights.

The criticisms of EU-ETS for airlines inspired CORSIA, a global framework to address CO_2 emissions from aviation. It represents the first global market-based measure, providing a unified approach to mitigate emissions from international aviation, complementing the areas not fully covered by EU-ETS. Airlines can reduce their carbon-offsetting requirements by implementing fuel-efficient technologies and practices, optimizing flight operations and routes, using SAF, and investing in more fuel-efficient aircraft. Remaining CO_2 emissions can be offset by purchasing emission units from the carbon market.[85] CORSIA differs from EU-ETS, as it is purely an offsetting system, not a cap-and-trade one. It is set to become fully operational in phases, starting with a voluntary period (2021–2026) before becoming mandatory for most ICAO member states in 2027. Airlines in Europe adhere to the EU-ETS for intra-European flights and CORSIA for international flights.

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[84] **Battle brews over climate law credits for aviation biofuels | E&E News**

[85] **Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) | ICAO**

However, CORSIA has met with a range of criticisms that shed light on its potential limitations and areas for improvement. First, its reliance on carbon offsets as a primary means of carbon abatement raises concerns about its effectiveness in encouraging direct, in-sector emissions reductions. The relatively low cost of carbon offsets compared to the investment required for fuel-switching or adopting alternative fuel technologies might deter airlines from pursuing more substantive emission reduction strategies.[86] On the other hand, CORSIA's dependence on a specified list of approved carbon credits brings into question its scalability, especially considering the aviation sector's growth and the increasing demand for carbon offsets. The potential for intensified competition for these offsets, driven by commitments under the Paris Agreement, underscores the importance of ensuring a sufficient supply of high-integrity offsets that can meet the industry's needs without compromising environmental goals.[87]

Another aspect of CORSIA is its "sectoral" approach in the initial phase, which calculates each airline's offset requirements based on the industry's total emissions growth since 2020, rather than individual emissions reductions. This means that an airline's obligation to buy offsets is proportional to its share of the industry's emissions, not its own emission reductions.[88] The intention is to share the burden of offsetting the sector's growth across all airlines, allowing newer carriers from rapidly developing regions to expand. However, this collective approach raises a concern: airlines making significant reductions in their emissions might not see a corresponding decrease in their offsetting requirements if the industry's overall emissions continue to rise. This situation could weaken the incentive for individual airlines to reduce emissions aggressively, as their efforts may not significantly impact their offsetting obligations due to the sector-wide calculation basis. These critiques suggest a need for closer examination of CORSIA's mechanisms to ensure they effectively encourage in-sector reductions.

Finally, as CORSIA is scheduled to conclude in 2035, questions linger over whether the anticipated development and deployment of SAFs and other emerging technologies will sufficiently advance to negate its necessity beyond this date.

The US Renewable Fuel Standard (RFS) program is another example of a market-based measure that can help promote SAF. Created under the Energy Policy Act of 2005, RFS is a national policy that requires a certain volume of renewable fuel to replace or reduce the quantity of petroleum-based transportation fuel, heating oil, or jet fuel. The program is administered by the EPA, which sets volume requirements and tracks compliance through the Renewable Identification Number (RIN) system. Obligated parties, such as oil refiners and importers, must meet these requirements by selling biofuel volumes or purchasing RINs.[89] Noncompliance results in hefty penalties from the EPA.

Some state governments have also created market-based measures that promote SAF, with California and Washington State being prominent examples. In California,

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[86] **ICAO's CORSIA Scheme Provides a Weak Nudge for In-Sector Carbon Reductions | ICCT**

[87] **Airlines' emissions reduction program faces shortage of carbon credits | E&E News**

[88] **Corsia: The UN's plan to 'offset' growth in aviation emissions | CarbonBrief**

[89] **Overview for Renewable Fuel Standard | EPA**

the Low Carbon Fuel Standard (LCFS) is designed to reduce the carbon intensity of transportation fuels. It aims to achieve a 20 percent reduction by 2030 from a 2010 baseline by setting a declining annual target for fuel suppliers. It has categorized SAF as an opt-in fuel since 2019, meaning that although refiners are not mandated to reduce the carbon intensity of jet kerosene, SAF producers can generate and sell LCFS credits to obligated parties. These credits create a financial incentive to produce and use SAF. However, SAF adoption has been modest, possibly due to the more lucrative nature of renewable diesel production, which competes with SAF in the market.[90] Washington State introduced its Clean Fuel Standard in July 2023, a program with similar goals. It requires fuel suppliers to reduce the carbon intensity of transportation fuels to 20 percent below 2017 levels by 2034. They can achieve this through various methods, including producing and blending low-carbon biofuels into their fuels and purchasing credits from low-carbon fuel providers.[91]

8.1.3. R&D Investment

Government investment in R&D projects can promote producing and using SAF by fostering innovation in production technologies, improving the efficiency and cost-effectiveness of production, and ensuring quality and scalability. Notably, public–private partnerships can leverage government support and industry expertise to enable research, investment, and regulatory efforts that are essential for scaling up SAF production and making it a commercially competitive alternative to conventional aviation fuels.

In 2020, the DOE Advanced Research Projects Agency-Energy announced $16.5 million in funding for six projects as part of the Systems for Monitoring and Analytics for Renewable Transportation Fuels from Agricultural Resources and Management program.[92] These projects will develop technologies that bridge the data gap in the biofuel supply chain by quantifying feedstock-related GHG emissions and soil carbon dynamics at the field level.

In 2021, the US DOE, DOT, Department of Agriculture (USDA), and other federal agencies launched a governmentwide SAF Grand Challenge to meet the demand by working with stakeholders to reduce costs and expand production and use to achieve a minimum of a 50 percent reduction in life-cycle GHGs compared to conventional fuel. The goal is to supply at least 3 billion gallons of SAF per year by 2030 and, by 2050, sufficient SAF to meet 100 percent of aviation fuel demand, which is projected to be around 35 billion gallons per year.[93] In 2022, USDA announced plans to invest more than $3.1 billion for 141 projects, some of which support farmers with climate-

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[90] **Will California Rise to the Biden Administration's SAF Grand Challenge? | ICCT**

[91] **Clean Fuel Program Rule | Washington State Legislature**

[92] **ARPA-E Announces $16.5 Million for Technologies Supporting the Biofuels Supply Chain | ARPA**

[93] **Memorandum of Understanding sustainable aviation fuel grand challenge | DOE, DOT, and USDA**

smart agriculture practices and research and fuel producers with carbon modeling components of aviation biofuel feedstocks.[94] Since 2021, the EPA and DOE have collaborated to speed up the regulatory approval for new fuels and feedstocks under RFS. Their joint efforts involve gathering data, analyzing technical details, and taking steps to quicken approvals, enabling these new resources to qualify for generating RINs.

Finally, the US National Aeronautics and Space Administration (NASA) is engaging with industry, academia, and other agencies through the Sustainable Flight Partnership to work on advanced vehicle technologies, efficient airline operations, and SAF.[95]

8.1.4. Mandates

Government mandates that require a certain percentage of SAF to be blended with traditional aviation fuels can push development and adoption. In 2023, the European Union set a mandate: as of 2025, it must account for at least 2 percent of aviation fuels used for the flights departing from EU. This minimum increases every five years, to 5 percent in 2030, 20 percent in 2035, 32 percent in 2040, 38 percent in 2045, and 63 percent in 2050. It has a specific submandate for e-fuels—synthetic fuels produced via PtL technology—which will need to be 0.7 percent by 2030, 5 percent by 2035, 8 percent by 2040, 11 percent by 2045, and 28 percent by 2050.[96]

8.1.5. Taxes on Fossil Fuels

Imposing taxes on fossil fuels can incentivize the production and usage of SAF by increasing the cost of conventional jet fuel and making SAF more economically attractive for airlines. By stimulating the demand for SAF, fossil fuel taxes can encourage investment in its production.

In 2021, the European Union proposed to introduce minimum tax rates to polluting aviation fuels as a part of its “Fit for 55” package.[97] In addition to stimulating the demand for SAF, this policy could make low-carbon transport, such as electric trains, more cost-competitive with fossil fuel–based flights and raise revenues that governments could invest in clean transport. However, fossil fuel taxes are politically difficult to implement because they could increase the cost of living, contribute to overall inflation, and lead to public dissatisfaction. The EU proposal has faced concerns that the elevation in fuel costs might affect voter sentiment.[98]

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[94] **Partnerships for Climate-Smart Commodities | US Department of Agriculture**

[95] **Sustainable Flight National Partnership | NASA**

[96] **Fit for 55 and ReFuelEU Aviation | EASA**

[97] **European Commission aviation pollution tax proposal fuels debate | UNEP**

[98] **EU attempt to tax polluting aviation fuel hits impasse | Reuters**

8.2. Policies to Advance Aircraft Technologies

8.2.1. Emission Standards

Strict emission standards can push aircraft manufacturers to allocate resources toward R&D projects, ensuring that their products meet or surpass the regulatory benchmarks, to address aviation's contribution to air pollution and GHG emissions.

At the international level, the ICAO has established standards for aircraft engine emissions since 1981, focusing on pollutants like unburned hydrocarbons, CO, NO_x, smoke, and fuel venting, particularly during the LTO cycle.[99] The standards have been updated periodically, with CAEP/2 through CAEP/8 reflecting the progressive tightening of limits from 1993 through 2011. They are part of ICAO's Annex 16, Volume II, and apply to aircraft turbofan or turbojet engines with rated thrusts greater than 26.7 kiloNewtons (kN), including most commercial passenger and freight aircraft.[100] The aim is to reduce aviation's environmental impact, focusing on local air quality, and, by assumption, the climate impacts of NO_x emissions at altitude.

Moreover, the ICAO introduced the CO_2 Emissions Standard in 2016, effective for new commercial and business aircraft from January 1, 2028, with a transition for modified aircraft beginning 2023. It calls for a 4 percent average decrease in cruise fuel consumption for new aircraft in 2028 relative to 2015 models, with specific reductions of 0–11 percent based on the aircraft's maximum takeoff mass.[101] It is meant to underpin the domestic regulations for countries that manufacture and certify aircraft, including the United States. However, ICAO does not directly impose penalties for noncompliance but relies on its member countries to implement and enforce the standards through their respective national aviation authorities, which can lead to inconsistent interpretation and implementation across countries.

In addition, in 2020, ICAO adopted a new standard for nonvolatile PM (nvPM) emissions from aircraft engines.[102] Effective from 2023, it applies to both newly designed and currently produced engines with a rated thrust exceeding 26.7 kN; these engines are responsible for a substantial share of the industry's particulate emissions. The requirements are stricter for engines that are newer or have a thrust of more than 150 kN. Moreover, the standards include a "no-backsliding" rule to prevent reintroducing older, less efficient technologies that emit more nvPM.

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[99] **ICAO Standards and Recommended Practices: Annex 16, Volume II | ICAO**

[100] See **ICAO Aircraft Engine Emissions Databank | EASA** for details on these standards.

[101] **International Civil Aviation Organization's CO_2 Standard for New Aircraft | ICCT**

[102] **ICAO Council adopts important environmental standard | ICAO**

The EPA established the PM and NO_x standards for aircraft engines in 1997. These are applicable to gas engines with rated thrusts exceeding 26.7 kN. The EPA aligned its NO_x standards with ICAO guidelines in 2005[103] and updated its nonvolatile PM standards in 2022[104] to include PM mass, number, and concentration measurements, to maintain the competitiveness of US manufacturers in the global market.

The EPA also set standard for GHG emissions (CO_2 and N_2O) in 2021,[105] after an endangerment finding in 2016 that confirmed that certain classes of aircraft engines contribute to GHG emissions that threaten public health and welfare.[106] These standards encompass commercial aviation and large business jets designed after January 2020 or in production by 2028. Despite explicitly aligning with the CO_2 emissions standards set by ICAO in 2017, the EPA has projected no emission reduction because, at the time of adopting the ICAO standards, manufacturers had already developed or were developing technologies to ensure compliance. Critics argue that adding a rule that is now outdated represents a missed opportunity for the EPA to establish regulations that could effectively reduce aviation's impact on public health and welfare.[107]

Although CO_2 is (now) regulated as a cruise pollutant, NO_x and nvPM are regulated at the LTO level instead, despite the health and climate impacts of cruise emissions. Coregulating NO_x and CO_2 emissions is challenging, as the efforts to reduce one type can sometimes lead to increases in the other, creating a trade-off that demands careful consideration (Skowron et al. 2021).

8.2.2. R&D Investments

Government investment in R&D can enable the exploration of new materials, designs, and technologies that can improve fuel efficiency of jet-fueled aircraft. It also plays a crucial role in advancing early-stage technologies, where the private sector may underinvest due to knowledge spillovers and uncertainty of return. Recognizing this, several US government agencies have intensified R&D activities to create new technologies to achieve at least a 30 percent improvement in aircraft fuel efficiency.[108]

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[103] **Control of Air Pollution from Aircraft Engines: Emission Standards and Test Procedures 2005 | EPA**

[104] **Control of Air Pollution from Aircraft Engines: Emission Standards and Test Procedures 2022 | EPA**

[105] **Regulations for Greenhouse Gas Emissions from Aircraft | EPA**

[106] **Finding That Greenhouse Gas Emissions from Aircraft Cause or Contribute to Air Pollution That May Reasonably Be Anticipated to Endanger Public Health and Welfare | EPA**

[107] **EPA's New Aviation Emissions Standard: Why It's Already Obsolete | Environmental & Energy Law Program**

[108] **FACT SHEET: Biden Administration Advances the Future of Sustainable Fuels in American Aviation | The White House**

In 2021, FAA launched the third phase of its Continuous Lower Energy, Emissions, and Noise (CLEEN) Program—a long-term public–private partnership begun in 2010 to help develop environmentally sustainable aircraft technologies.[109] This cost-sharing approach enables industry to undertake higher risks and strengthens the business case for advancing new technologies. Under CLEEN Phase III, FAA has awarded more than $100 million to aircraft and engine companies, such as General Electric Aviation and Boeing, with goals of reducing CO_2 emissions by improving fuel efficiency by at least 20 percent below the relevant ICAO standard, NO_x emissions by 70 percent relative to the most recent ICAO standard, PM emissions below the ICAO standard, and noise by 25 dB cumulative relative to the FAA Stage 5 standard.[110]

The Department of Defense has invested in several programs to enhance the efficiency of existing military aircraft and develop new energy-efficient aircraft. Some long-term programs include Air Force B-52 Commercial Engine Replacement Program, Army Improved Engine Turbine Program, and Adaptive Engine Transition Program and Next-Generation Adaptive Propulsion Program to upgrade the aging engines for B-52 bombers, Apache and Black Hawk helicopters, and fighter jets, respectively.

The 2021 Bipartisan Infrastructure Law established $8 billion funding for the Regional Clean Hydrogen Hubs program, which can help address key challenges in production, vital for advancing aircraft technologies. This funding is also crucial for advancing PtL technology for SAF, as green hydrogen production is a fundamental step in this process. Administered by the DOE, this program aims to establish at least four hubs. It focuses on enhancing the entire hydrogen supply chain—production, processing, delivery, storage, and end use—by creating networks of hydrogen producers and consumers supported by necessary infrastructure.

In 2022, the US FAA and its aviation industry partners also launched the Eliminate Aviation Gasoline Lead Emissions initiative to phase out leaded aviation fuels in piston-engine aircraft by 2030. The strategy includes identifying at least one unleaded fuel that is safe for the General Aviation fleet, addressing the safety and technical challenges for high-performance engines using unleaded fuels, and supporting the increased production and distribution of unleaded alternatives. Additionally, the initiative aims to ensure the availability of 100 low-lead fuel—which has lower lead content than older fuels—during the transition, develop policies for airport infrastructure funding to accommodate unleaded fuel and endorse plans that reduce or eliminate reliance upon leaded aviation fuels.[111]

In 2023, NASA awarded Boeing $425 million over seven years for the Sustainable Flight Demonstrator project to build and test a Transonic Truss-Braced Wing demonstrator airplane, which can reduce fuel consumption and emissions by up to 30 percent

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[109] **Continuous Lower Energy, Emissions, and Noise (CLEEN) Program | FAA**

[110] **FAA Awards $100M to Develop Next Generation of Sustainable Aircraft Technology | FAA**

[111] **Building an Unleaded Future by 2030 - Eliminate aviation gasoline Lead emissions | FAA**

compared to today's most efficient single-aisle airplanes, potentially revolutionizing commercial airliner efficiency.[112] Also, in collaboration with NASA, DOE is investing $115 million to advance the battery technologies capable of attaining the required energy density for near term eVTOL and short-range consumer aircraft applications. These advancements also could achieve the energy density necessary for longer-range electric aircraft in the long term.[113]

However, the investment in R&D for electric and hydrogen aircraft remains limited compared to similar technologies in ground vehicles. Aviation presents its own set of challenges that differ significantly from road vehicles. For electric aviation, this includes additional research into specialized battery technology and charging solutions tailored to its specific needs. For hydrogen aviation, further research is necessary to adapt fuel-cell technology to the unique pressure and temperature conditions of aircraft.

8.2.3. Incentives

Government incentives for R&D, demonstration, and deployment of alternative aircraft technologies like hydrogen and electric, especially for short-haul travel, have strong economic justifications. These aircraft types offer a sustainable solution to aviation's environmental challenges by reducing or eliminating tailpipe emissions. Studies have even suggested that the emission reductions from eVTOL for short-haul flights might surpass those of electric cars (Sripad and Viswanathan 2021). Additionally, these technologies are much quieter than traditional aircraft. R&D could lead to advancements, potentially increasing their range and passenger capacity and making them viable for longer distances. However, innovation spillovers in such nascent technologies, where advancements made by one manufacturer can benefit others, discourage private investments, as firms may not fully capture the benefits of their innovations. Government incentives can mitigate this challenge and ensure the effective development and scaling of these technologies by supporting the entire spectrum from research to deployment.

The US incentives for electric aircraft have been limited and lag far behind that of ground electric vehicles (EVs). Tax credits, which have been effective in promoting ground EV technology, are notably absent for electric aircraft. Programs under the IRA, such as the Advanced Energy Project Investment Tax Credit (ITC) and Advanced Manufacturing Production Tax Credit (PTC), only apply to on-road vehicles. Expanding these incentives to include aviation could significantly bolster their development and integration into the broader transportation sector.

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[112] **NASA awarding Boeing $425M over 7 years for Sustainable Flight Demonstrator project; Transonic Truss-Braced Wing concept | Green Car Congress**

[113] **FACT SHEET: Biden Administration Advances the Future of Sustainable Fuels in American Aviation | The White House**

8.3. Policies to Change Consumer Behavior

Government policies can also encourage consumers to make more sustainable travel choices, such as less flying, ground transportation for domestic travel, greener flights, and carbon offsets.

8.3.1. Improve Train and Bus Infrastructure

Governments can provide viable alternatives to short-haul flights by investing in alternative modes of transportation that are more fuel efficient,[114] such as high-speed rail. According to Project Drawdown,[115] it can cut carbon emissions by as much as 90 percent when compared to conventional modes, such as driving, flying, or standard rail travel, making it the most expedient means of transportation for distances of a few hundred miles. Furthermore, high-speed rail systems contribute to bolstering resilience and essential backup capabilities in confronting climate change, such as when flights are canceled due to extreme weather conditions.

A complementary policy could be to restrict flights on train-servable routes. For instance, France banned air travel on routes that can be traveled in less than 2.5 hours by high-speed rail in 2021 as a part of comprehensive climate legislation.[116] However, the viability of this policy varies across regions. For instance, rail alternatives may not be viable in remote corners of Alaska with limited potential users or in regions such as Indonesia and the Philippines with several islands.

8.3.2. Taxes on Passenger Flights

Taxing passenger flights increases their cost, incentivizing people to fly less frequently or choose alternative transportation. For example, the United Kingdom introduced an Air Passenger Duty (APD) in 1994—a tax on passenger flights from UK airports. Table 3 summarizes the APD rates as of 2024.[117]

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[114] **Why the US needs to get on track with high-speed rail | Greenbiz**

[115] **High-speed Rail | Drawdown**

[116] **France has banned air travel between cities that can be reached easily by train | Business Insiders**

[117] **Rates for air passenger duty | GOV.UK**

Table 3. APD Rates from April 1, 2024

Destination bands	Reduced rate	Standard rate	Higher rate
Domestic	£77	£14	£78
Band A	£13	£26	£78
Band B	£88	£194	£581
Band C	£92	£202	£607

Data source: Government of the United Kingdom

Notes: The reduced, standard, and higher rates apply to economy class, premium economy and first class, and planes of 20 tonnes or more equipped to carry fewer than 19 passengers, respectively. Bands A, B, and C apply to international flights of up to 2,000 miles, 2,001–5,500 miles, and more than 5,500 miles, respectively.

Several other European countries have implemented or are planning to introduce aviation taxes and charges to promote sustainable travel. Norway, Sweden, the Netherlands, and Denmark have implemented passenger charges and taxes of $7.4–42.3 depending on whether the destinations are within or outside of Europe;[118] France is considering raising taxes on airline tickets to fund investments in train infrastructure and enhance the appeal of rail travel.[119]

More generally, Pigouvian transport pricing can be used to directly price the externalities, such as air pollution and climate impact, into the cost of each mode of transportation. This policy can encourage more efficient and sustainable transport behavior by allowing passengers to internalize their external transportation costs. Hintermann et al. (2021) provide an example; through a large-scale randomized controlled trial in Switzerland, they show that giving passengers a financial incentive to reduce their external transport costs can significantly change their behavior.

However, taxes on passenger flights have several disadvantages. The APD is criticized for not reflecting flights' actual carbon emissions or encouraging airlines to invest in more efficient aircraft or other sustainable practices. Moreover, it could increase travel costs and negatively affect the airline and tourism industry, potentially leading to job losses and reduced economic growth.[120]

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[118] **Taxes & the environment Fact Sheet | IATA**

[119] **France to increase taxes on airline tickets to support investments in train infrastructure | Aviation24.be**

[120] **Are Aviation Taxes an Effective Answer To Climate Change? | Simple Flying**

Discussion is growing about a frequent-flyer tax, because a small group is responsible for most flight emissions in most countries.[121] The New Economics Foundation suggests replacing the flat-rate APD, which charges £13 for economy flights of up to 2,000 miles and £78 for more than 5,500 miles, with a progressive version that would increase for each additional flight an individual takes beyond their first in a year, potentially making single annual trips more economically accessible. The foundation's analysis indicates that the average annual payment for the bottom and top 20 percent income groups would be around £7.75 and £165.85, respectively.[122] Although no country has implemented a frequent-flyer tax yet, it is viewed as a potential approach to more equitably distribute the climate footprint associated with aviation among different flyers.

8.3.3. Voluntary Carbon Offsets

VCOs are vital for reducing the aviation sector's carbon emissions. They enable stakeholders to offset their GHG emissions by investing in projects that reduce or remove carbon from the atmosphere. However, regulating the VCO markets is important to ensure their effectiveness and reliability; it can help validate the authenticity and environmental benefits of carbon offset projects, prevent fraud and inefficiency, and standardize the market, aiding buyers in comparing and understanding different options.

The UK Quality Assurance Scheme for Carbon Offsetting was introduced in 2009 to provide consumers with better information and assurance about VCOs, using a quality kitemark to indicate compliance. The government's goal was to establish rigorous governance procedures and processes for VCOs to ensure that consumers' investments are reliable and effective, addressing the concern that products may not deliver the environmental benefits they claim. However, the voluntary offset industry largely resisted, challenging the government's regulatory role and its expertise in offsetting (Lovell 2010). This situation shows the complex relationship between the public and private sectors in carbon offset governance.

In 2022, ICAO created guidelines to help airlines incorporate carbon offsetting into its strategies for reducing CO_2 emissions. These guidelines provide a framework for a program where offsets can come from activities such as tree planting, forest conservation, capturing methane from landfills, and carbon capture and storage.[123]

In 2023, California introduced the Voluntary Carbon Market Disclosures Business Regulation Act. Effective January 1, 2024, it is the first binding US regulation specifically targeting the voluntary carbon market. It applies to entities in California involved in marketing or selling VCOs or making claims about net-zero emissions, carbon neutrality, or significant carbon emission reductions. It aims to regulate and bring transparency to the VCO market, ensuring accountability and accurate information about carbon

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[121] **Hot topic: should we tax frequent flyers? | National Graphic**

[122] **A frequent flyer levy- sharing aviation's carbon budget in a net zero world |New Economic Foundation**

[123] **Aviation Carbon Offsetting Guidelines for Voluntary Programs | ICAO**

reduction efforts.[124] Penalties are civil fines of up to $2,500 for each day that required information is not made available or is inaccurate, with total penalties up to $500,000. However, critics argue that the statutory text is relatively brief and leaves several key concepts undefined.

8.4. Changes in Corporate Travel Policies

Corporate policy changes can also play a crucial role in addressing the environmental impacts of aviation by addressing frequent business travel. By promoting virtual meetings, opting for lower-emission transportation, and restricting nonessential travel, companies can substantially reduce their travel footprint and environmental impact.

The T&E “Travel Smart” campaign aims to reduce corporate air travel emissions by 50 percent from pre-COVID levels by 2025.[125] According to T&E, business travel accounts for an estimated 30 percent of air travel in Europe, and a 50 percent reduction in corporate travel in Europe could decrease emissions by 32.6 $MtCO_2$ by 2030.[126] This is comparable to removing 16 million polluting cars from the roads. The campaign employs several methods, including the Travel Smart Ranking, which evaluates 322 businesses globally on their efforts to lessen and report corporate air travel emissions. The campaign suggests that companies consider shifting from air to rail travel where possible and use videoconferencing for long-haul meetings.

8.5. Policies to Build Sustainable Airports

Policies can encourage airports to adopt green practices, such as building eco-friendly infrastructure, using zero-emission ground transport, and optimizing energy consumption. These measures not only reduce carbon emissions but also help mitigate noise pollution, conserve resources, and improve air quality for passengers and nearby communities.

The FAA supports various climate and environmental initiatives for airports through funding programs.[127] For instance, the FAA’s Voluntary Airport Low Emissions Program provides financial support for acquiring low-emission vehicles, establishing refueling and recharging stations, gate electrification, and additional initiatives aimed at enhancing air quality at airports located in nonattainment areas.

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[124] **Assembly Bill No. 1305 - Chapter 365 | California Legislative Information**

[125] **Travel Smart Campaign | Travel Smart**

[126] **What is the impact of corporate travel on aviation emissions? | Transport & Environment**

[127] **Airports Climate Challenge: Table of Relevant FAA Funding Programs | FAA**

The US IRA has enhanced the ITC[128] and PTC[129] for renewable energy investments. The ITC now offers a 30 percent credit for projects under 1MW and larger projects that meet specific labor criteria; the PTC provides a credit based on the system's yearly energy output, up to 2.6 cents per kWh for 10 years. Importantly, the IRA allows tax-exempt entities, such as airports, to receive direct reimbursements, including the 30 percent incentive for renewable energy and battery storage projects.

Additionally, the IRA introduced tax credits for commercial clean road vehicles, enabling airports to receive up to $40,000 in credits for purchasing qualified vehicles.[130] This credit is calculated as the lesser of 15 percent of the vehicle's cost (30 percent for non-gas/diesel vehicles), the vehicle's incremental cost, or a maximum of $7,500 for vehicles with gross vehicle weight ratings less than 14,000 pounds and $40,000 for heavier vehicles.

Policies can play a significant role in establishing infrastructure for electric and hydrogen aviation. For instance, incentives and reforms could streamline environmental reviews under the National Environmental Policy Act and California Environmental Quality Act, facilitating the development infrastructure for these technologies.

8.5.1. Policies to Promote Accountability of Countries

Effective management of aviation bunker emissions is crucial for reducing the impact of global emissions from international air travel. Recent advancements in technology, operational improvements, and SAF are contributing significantly to this effort. These developments are complemented by policy measures, such as EU-ETS for intra-European flights and CORSIA for global flights.

Although these initiatives primarily focus on the aviation industry, particularly airlines, acknowledgment is increasing of the need for country-level engagement to comprehensively address aviation emissions within broader climate policies. In 2022, at its 41st Assembly, ICAO established a long-term global aspirational goal (LTAG) for international aviation to reach net-zero carbon emissions by 2050, aligning with the Paris Agreement. This goal encourages nations to independently reduce emissions from international aviation. However, acknowledging each country's unique circumstances and capabilities, it does not impose specific emission reduction targets or mandate them to achieve reductions.[131]

Within the framework of the Paris Agreement, including international aviation emissions in NDCs is being discussed as a strategy for comprehensive emissions accounting. The Paris Agreement obliges member states to establish "economy-wide

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[128] **IRA Section 13702 – Clean Electricity Investment Credit | IRA Tracker**

[129] **IRA Section 13101 – Production Tax Credit for Electricity Produced from Certain Renewable Sources | IRA Tracker**

[130] **IRA Section 13403 – Clean Commercial Vehicle Credit | IRA Tracker**

[131] **Long term global aspirational goal (LTAG) for international aviation | ICAO**

absolute emission reduction targets," aimed at keeping the global temperature rise significantly below 2°C. The EU and its 27 member states include emissions from all outgoing flights in their NDCs.[132] Furthermore, environmental advocacy organizations are urging other countries to revise their NDCs to encompass all emissions from aviation.[133, 134]

However, attributing international carbon emissions to individual countries is complex and unclear. The UNFCCC originally presented eight allocation options for international bunker fuels in 1996, varying from allocating based on where the fuel was sold to considering the country of departure or destination[135] and leading to varied distribution of responsibilities across countries. For instance, allocating based on fuel sales could disproportionately affect hub countries, such as the United Kingdom and Germany, and using the country of departure could overstate emissions from countries such as Iceland and Portugal, where tourism is a significant factor. These disparities underscore the challenge of establishing a globally acceptable attribution system.

9. Open Questions

9.1. Questions Related to Sustainable Aviation Technologies

9.1.1. Traditional Aircraft Technologies

Several policy-relevant questions on efficient aircraft technologies merit exploration. One pertains to the optimal timing for fleet replacement. Newer models often feature advanced technologies that enhance fuel efficiency and reduce noise and emissions. From an airline's viewpoint, the ideal replacement time is when the costs of maintaining and operating an older model become higher than the advantages of a newer, more efficient one, considering factors such as safety, fuel prices, maintenance costs, and resale value. In contrast, from a social planner's perspective, the optimal time balances the economic and environmental benefits of a new aircraft against the environmental impacts of its production and disposal. Conflicts can arise between the two. For example, updating fleets more frequently to incorporate the latest fuel-efficient technologies might be more environmentally beneficial but not always practical.

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[132] **Update of the NDC of the European Union and its Member States | UNFCCC**

[133] **Shipping and aviation are subject to the Paris Agreement, legal analysis shows | Transport & Environment**

[134] **Aviation and shipping emissions and national climate pledges | Transport & Environment**

[135] **United Nations Framework Convention on Climate Change: "Communications from Parties Included in Annex I to the Convention: Guidelines, Schedule and Process for Consideration." Section III: Allocation and Control of International Bunker Fuels | UNFCCC**

Further research is needed to determine the best timing for fleet replacement, also considering external factors such as supply chain disruptions. The aviation aftermarket, which provides MRO services for aircraft after their original sale, has grown by 18 percent in 2022, reaching an estimated $125 billion, partly due to supply chain issues affecting new aircraft production.[136] Under this trend, what are the costs and benefits of replacing the oldest in-use aircraft with the most fuel-efficient ones available? What about retrofitting parts of aircraft with more sustainable ones? Given positive benefits, what policies can effectively incentivize airlines to replace or retrofit old aircraft? Understanding the balance between the environmental benefits of operating newer, more efficient aircraft and potential costs associated with manufacturing and fleet renewal is crucial in the context of CORSIA, which incentivizes airlines to reduce emissions without specifically addressing impacts from aircraft manufacturing.

Comprehensive research is necessary to fully understand the effects of aircraft emissions, including NO_x, CO_2, and particulates. This research can cover characterizing and quantifying emissions, examining their impact on air quality, atmospheric chemistry, and public health, modeling and predicting accurately, and analyzing the economic impacts of emission reduction technologies. An integral part of this research involves evaluating regulations and exploring new policy measures. Despite ongoing efforts to regulate emissions and enhance aviation fuel efficiency, a significant gap remains in comprehending their actual efficacy. Thorough research is imperative to assess the real-world effectiveness of these policies. For instance, how have regulatory standards, such as those set by ICAO and the EPA, influenced aircraft manufacturers' decisions to invest in more fuel-efficient and environmentally friendly technologies?

Furthermore, this research should also extend to strategies aimed at mitigating the formation of contrails, thereby addressing the aviation sector's non-CO_2 climate impacts. Although pivotal in tackling aviation's climate footprint, policies like EU-ETS and CORSIA currently overlook the issue of contrails. The difficulty in regulating them arises from their formation under certain atmospheric conditions, which are highly variable and unpredictable, making it challenging to forecast their occurrence. In a recent pilot project, American Airlines and Google utilized artificial intelligence to develop forecast maps for contrail formation, enabling pilots to adjust flight altitudes strategically, just as they adjust altitude to avoid turbulence. This method cut contrail formation by 54 percent in the test flights but required 2 percent more fuel; planes are most efficient at higher altitudes where air is thinner, but contrails are also more likely to form at these altitudes (Arnold 2023). This finding shows that commercial flights can reduce climate impact by avoiding contrails. The EU-funded BeCoM project is also working to predict the precise location and timing of contrail formation to mitigate its climate impact.[137] Research can help develop optimization algorithms that minimize environmental impact by balancing contrail avoidance with fuel efficiency. Additionally, research and policy engagement could guide the creation of incentives for airlines to reduce contrail formation. An example worth considering is whether frameworks like CORSIA could be modified to encourage airlines to actively minimize contrail generation.

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[136] **Global fleet and MRO market forecast 2023-2033 | Oliver Wyman**

[137] **Better Contrails Mitigation | European Commission**

9.1.2. Sustainable Aviation Fuel

Research can play a pivotal role in enhancing the deployment of SAF by identifying the challenges in feedstock availability and proposing solutions to mitigate them. One area where research is particularly valuable is optimizing resource allocation. Given the competition for feedstock and biorefinery capacity between renewable diesel and SAF, what strategies can maximize carbon mitigation benefits from biofuels? A practical example is understanding how to balance resource use considering the shift toward electric transportation, ensuring that biofuels are used where they have the greatest impact.

Research can play a vital role in identifying the required infrastructure investments and exploring effective financial models to guide governmental investment strategies for supporting SAF. Additionally, it can aid in assessing the pros and cons of varied policy methods for SAF promotion. Regions have approached SAF support differently, with Europe opting for mandates and the United States leaning towards incentives. This diversity raises questions about the sustainability and optimal timing of these policies: How long should the incentives last? When does it become advantageous, or even necessary, to shift from temporary incentives to more permanent mandates? Additionally, how effective are regional policies like LCFS in driving substantial investment and innovation in the SAF? Do these policies merely result in negligible improvements, or can they genuinely stimulate meaningful industry shifts?

The broader market effects of these policies also demand careful consideration. Barbot et al. (2014) found that EU-ETS would impede competition within the market and deter free entry of airlines. Similarly, research can delve into the repercussions of SAF mandates or incentives on airlines' profitability and ticket prices. Such insights could help formulate policies that enhance SAF's competitiveness against other biofuels used in road transport without excessively inflating the cost of air travel, and ensuring an efficient, cost-effective and equitable transition to SAF.

More research is also needed to fully understand the wide-ranging environmental and health effects of producing and using SAF, importantly the effect of agricultural feedstock on ILUC. While it is hypothesized that specific feedstocks could lead to deforestation and may result in significant emissions, research on ILUC is notably lacking. Analyzing the historical influence of different SAF feedstocks on these outcomes can guide the development of policies that minimize environmental harm. Section 3 highlights how the lack of scientific agreement leads to varying evaluations of sustainability and emissions reductions from different SAF options. Research using up-to-date data and scientific understanding can mitigate these differences. Research can also help identify sustainable practices in feedstock production and find effective ways to incentivize their adoption. It is also crucial to continually update this research to incorporate technological progress.

Further research is necessary to compare PtL fuels with crop-based biofuels, considering their tradeoffs: biofuels may cause indirect land use changes, while PtL is currently energy-intensive. Additionally, the use of industrially captured carbon in PtL—potentially cycling carbon back to the atmosphere—merits deeper investigation for its real environmental impact. Considering these factors, it is crucial to assess whether PtL's advantages sufficiently outweigh those of biofuels, factoring in the alternative uses of renewable energy and hydrogen and evaluating the effectiveness of carbon usage in PtL versus direct sequestration. Importantly, it is crucial to identify what innovations or developments are necessary for PtL to surpass biofuels in terms of environmental impact and efficiency.

In addition to contributing to climate change mitigation, SAF can improve air quality and health outcomes. For instance, Arter et al. (2022) demonstrated that 50 percent SAF blends can reduce premature mortalities from $PM_{2.5}$-attributable LTO emissions by up to 18 percent. However, a need remains for similar analyses of emissions for entire flight durations. Evaluating SAF's total environmental and health impacts throughout complete flight cycles is essential for promoting its broader use in aviation.

9.1.3. Alternative Aircraft Technologies

Scaling hydrogen requires a feasibility assessment regarding deployment at a global scale. Initiatives such as "HyDeal Ambition" for expansive commercial production have marked significant progress in deployment efforts.[138] Yet, macro-level research is critically needed to scale renewable hydrogen to meet global needs, understand the intricacies of technology and infrastructure expansion, and develop policies that foster a strong renewable hydrogen market.

Hydrogen has several applications, such as fuel cells for electricity generation (Ozturk and Dincer 2020), vehicle fuel (Manoharan et al. 2019), industrial processes, such as refining and chemical synthesis (Griffiths et al. 2021), and energy storage (Mazloomi and Gomes 2012).

It is gaining attention as a cleaner energy alternative to fossil fuels, in not only aviation but also sectors such as trucking and shipping, as part of the push toward reducing carbon emissions (Gray et al. 2021). This versatility leads to potential competition for hydrogen among different sectors, especially as economies transition toward low-carbon energy sources. How will the increasing demand for hydrogen from various sectors affect its price and availability? What will be the effect of this competition for hydrogen on global carbon neutrality goals? What strategies can be implemented for efficient distribution among competing sectors? What emerging technologies hold the potential to significantly scale up production?

It is also essential to examine the potential impact of hydrogen aircraft on airline operations. This includes investigating the effect on flight patterns, refueling strategies, network design, and the feasibility of hub-and-spoke systems. A critical question is the associated cost of these transitions. For instance, a report by T&E estimates that around €299 billion will be needed from 2025 to 2050 to develop and

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[138] HyDeal Ambition is an industry platform bringing together 30 companies covering the complete green hydrogen value chain. For more details, see **https://www.hydeal.com/hydeal-ambition**

manage the hydrogen aviation value chain in Europe, with 83 percent of this cost going toward hydrogen production, distribution, and liquefaction.[139]

Research on hydrogen safety in aviation is also crucial, with the industry working to catch up with sectors such as automotive in hydrogen use. Experience in other areas suggests that hydrogen may not be more dangerous than kerosene, and its adoption in various applications outside aviation can demonstrate its safe use and operation[140] and help change public perceptions, vital for broader acceptance. However, although research on hydrogen safety in ground transport exists, aviation requires additional research, considering its unique challenges, such as the need for lightweight, compact, and highly efficient storage systems that can withstand various operating conditions. Kazula et al. (2023) provide an example by examining safety challenges and potential weaknesses of hydrogen fuel-cell systems in electrified aircraft propulsion, offering solutions, and analyzing the risks associated with cryogenic hydrogen fuel and high electrical energy. Moreover, as regulatory bodies, such as the FAA and EASA, are starting to establish guidelines for hydrogen use in aviation, research can play a crucial role in shaping them. For instance, Spencer (2023) explores how to certify future hydrogen airplanes, focusing on aspects such as flammability, ignition energy, cryogenic states, and crashworthiness. Collaboration among manufacturers, regulators, and researchers is key for developing regulations to ensure safe hydrogen use in aviation.

Research is pivotal in addressing environmental justice concerns, as highlighted by Dillman and Heinonen (2022), who point out possible social disparities across the hydrogen value chain. Predicting the societal impact of a growing hydrogen economy is complex due to the wide range of outcomes and uncertain technological advancements. Environmental justice advocacy groups have addressed these concerns by establishing equity principles for the DOE funding of hydrogen projects, emphasizing the need for community involvement in planning and implementing projects to avoid perpetuating existing injustices.[141]

As alternative technologies become widely available, research must also address how they can be made economically competitive with conventional jet-fuel aircraft. For instance, the T&E report finds that hydrogen aircraft could be cost-competitive, but this hinges on appropriate taxation and carbon pricing policies. It also states that by 2035, operating costs for a 1,000-nautical-mile flight on a hydrogen aircraft are projected to be 7.7 percent higher than a jet aircraft using an untaxed SAF/jet fuel blend but 2.1 percent lower if the blend is taxed, since the tax on the blend makes hydrogen relatively cheaper.

Furthermore, evaluating the life-cycle environmental impact of alternative aircraft technologies compared to conventional fossil fuel–powered aircraft is essential for fully understanding their ecological footprint. This analysis should focus on not only operational emissions but also the environmental costs associated with manufacturing

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[139] **The cost of hydrogen aviation | Transport & Environment**

[140] **Storage and safety: hydrogen aircraft's key challenges | yocova**

[141] **EJ groups develop guiding equity principles for department of energy's hydrogen infrastructure funding | CBE**

and retirement. Critical factors include sourcing materials for components, such as batteries, and the processes involved in disposing or recycling these components at the end of the aircraft's life. Additionally, although the benefits of these newer technologies include reduced GHG and improved noise and air quality around airports, it is also essential to consider the potential warming effects of contrails from hydrogen aircraft. Examining these aspects throughout the aircraft's life cycle can help make a more accurate assessment of the actual environmental benefits and guide policymakers toward sustainable aviation solutions.

Research is also pivotal in addressing critical questions regarding infrastructure requirements for hydrogen and electric aviation to assess their viability and necessary government support. This includes exploring whether hydrogen should be transported via pipelines to airports or generated on site and assessing the feasibility and benefits of airports establishing their own microgrids. Moreover, research can help compare the long-term infrastructure and operational demands of various transportation alternatives, including high-speed rail and hydrogen-powered aviation for routes under 2,000 km. With advancements, hydrogen technology could be sufficiently developed by 2035 to replace flights up to 3,500 km (Mukhopadhaya and Rutherford 2022), offering an alternative to the already viable high-speed rail.[142] Considering the substantial investments required for both options, determining which offers greater benefits is crucial, and this decision may differ based on the unique regional, economic, and environmental contexts involved.

Finally, research can help evaluate consumer attitudes toward emerging hydrogen and electric technologies. How might adopting these affect consumer behavior and preferences in air travel? Consumer surveys can provide insights and help policymakers design regulatory frameworks that effectively deploy and scale sustainable aviation technologies.

9.2. Questions Related to Consumer Behaviors

Understanding consumer behavior can help determine the direction of future policy initiatives promoting sustainable transportation choices. What factors govern the choice of mode of transport? Insights into factors such as ticket pricing, train/flight punctuality, and passenger comfort are critical building blocks. For instance, Su et al. (2019) find that passenger preference for air transport in the Beijing–Shanghai corridor decreases with the accompanying number of passengers and access time and increases with income. Women and younger travelers are more likely to fly, and leisure travelers, being price-sensitive, opt for air transport when prices are low. By shedding light on preferences for different characteristics, such as punctuality and ticket prices, research can help assess the potential of future high-speed trains and enhance existing ground transportation services to compete with air travel.

Equally crucial is deciphering consumer willingness to pay (WTP) for sustainable aviation. What is the WTP for lower-emitting flights or VCOs? Although several

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[142] **The Bullet Train to Lower-Carbon Travel | ICCT**

studies examine WTP for carbon emissions in various countries, their findings vary. For example, a stated-choice experiment in Italy found that the WTP of their sample of 1,228 Italians was €12–38 per ton and €14–66 per flight (Rotaris et al. 2020). However, a revealed-preference approach by Berger et al. (2022) found a median WTP of 0. This variation in WTP could arise due to methodological differences like stated versus revealed preferences, and other factors such as regional differences or personal values. For instance, Kim et al. (2014) suggest that a consumer's sense of belonging can impact participation in carbon-offsetting programs. This indicates a broad scope for further research to deepen our understanding of these variables.

Research can also help understand what nudges and incentives can shape consumer preferences toward reducing or offsetting travel emissions. For instance, Zhang et al. (2019) studied how message framing impacts air passengers' perceived credibility of aviation VCO messages. They discovered that messages highlighting the local community's environmental benefits from VCO programs are deemed more credible than those focusing on foreign countries. Such knowledge can empower policymakers to harness passenger preference for sustainable travel through potential cost-sharing mechanisms for SAF and other technologies.

Furthermore, research can help understand the impact of policies, such as aviation taxes and restrictions on train-serviceable routes, on passenger and airline behavior, ticket prices, and overall demand for air travel. Unlike VCOs, these policies are obligatory. Understanding their impact can help develop balanced policies that achieve environmental objectives without overly burdening stakeholders. For instance, Falk and Hagsten (2018) found that introducing flight departure taxes in Germany and Austria in 2011 led to a 5–9 percent reduction in passengers at affected airports in the first two years, disproportionately affecting the airports frequented by low-cost airlines, but regular hubs saw minimal effects. White et al. (2019) studied major tax changes in the US aviation industry and found that tax increases often result in fares rising more than the tax hike itself, suggesting a disproportionate burden on consumers.

An important area of inquiry involves identifying policies that can address the global disparity in air travel, where a small portion of the population accounts for most flights. In 2019, for example, the wealthiest 20 percent of individuals were responsible for 80 percent of flights, and just 2 percent of the world's population, those flying more than six times a year, contributed 40 percent of passenger miles.[143] This data underscores the importance of formulating policies that specifically target frequent flyers. Additionally, research aimed at corporate travel habits is needed, exploring how to shift the travel behaviors of this crucial group. Some relevant areas for research include understanding the role of loyalty programs in influencing flying frequency and identifying the impact of strategies, such as frequent-flyer taxes, on the travel habits of frequent flyers.

Finally, more research is needed on regulating VCOs to ensure that they represent accurate, additional, and verifiable emission reductions.

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[143] **Aviation Climate Finance Using a Global Frequent Flying Levy | ICCT**

9.3. Questions Related to Airport Emissions

The impact of airport operations on nearby populations is influenced by factors such as prevailing wind direction, flight frequency, aircraft types, airport management, and the area's demographics. Research plays a vital role in understanding and mitigating these impacts. For example, Yim et al. (2013) employed a multiscale air quality model to assess the impact of emissions from top 20 UK airports, finding that they contribute to about 110 early deaths annually. They also identified that measures such as desulfurizing jet fuel and electrifying GSE could mitigate up to 65 percent of these health effects. Schlenker and Walker (2015) revealed that increased airport congestion significantly raises local CO levels, with the effect decreasing over distance. Additionally, higher pollution levels correspond to notable increases in health issues, with asthma and respiratory problems rising by 17 percent and heart problems by 9 percent from the baseline. This type of research, which quantifies the benefits of green airport initiatives in the form of improved air quality or reduced noise, and the associated health impacts, is crucial for developing policies that support sustainable airport practices. As these impacts vary by airport, localized research is essential. Additionally, research into adequate financing and investment strategies for electrifying ground operations, such as LTO activities, can promote creating environmentally friendly airport infrastructure.

Research can help fine-tune airport operations to preserve passenger service quality while mitigating environmental impacts. Jalalian et al. (2019) illustrate this by proposing a bi-objective model that integrates flight scheduling, aircraft-path assignment, and gate assignment to improve CO_2 emissions and passenger service by up to 11 and 31 percent, respectively. Future research could explore balancing CO_2, PM, and NO_x emissions in aircraft operations to reduce environmental impact, as well as co-regulating them to address potential trade-offs. Given the uncertainties about the climate impacts of various factors, such studies need regular updates to incorporate new findings and technological progress.

Additionally, research can highlight ways to improve the setup of alternative technologies and electric aircraft systems at airports. For instance, Kinene et al. (2023) introduced an optimization model to help strategically plan the charging networks for electric aircraft and thus scale this technology. Their findings emphasize the advantages of underused regional airports, highlighting their connectivity and investment benefits. Guo et al. (2023) developed a dual-purpose framework for planning airport microgrids that can service both EVs in parking areas and electric aircraft. They found that vehicle-to-grid technology enhances the economic efficiency of the airport microgrid. Moreover, although direct plug-in charging generally offers greater microgrid resilience, the battery-swapping approach appears to lower operational costs. Further research on facilitating alternative technologies and SAF at the airports can guide policy to support these advancements.

Research and engagement with airports can help them adapt to electric and hydrogen aviation technologies. WSP, a prominent civil engineering group, exemplifies this by working with Philadelphia International Airport in vertiport planning. Their work addresses challenges such as planning for landside vertiports, which are crucial in early-adoption phases for short air taxi flights to simplify passenger and baggage processing.[144]

9.4. Questions Related to Countries' Responsibilities

Adequately attributing carbon emissions to individual countries remains a key issue. Research can play a pivotal role by comparing allocation methods and developing a globally acceptable mechanism. One innovative approach proposed by Larsson et al. (2018) suggests crediting emissions based on the passengers' country of residence. This method considers the number of international air trips by a country's residents, average distance of these trips, and GHG emissions per passenger kilometer. Such an approach could address the challenges associated with hub-centric allocation and the overrepresentation of emissions from tourist destinations, offering a more balanced and equitable distribution of carbon-offsetting responsibilities.

10. Conclusion

This report analyzes the various pathways for sustainable aviation, outlining the challenges, reviewing relevant US and global policies, and identifying areas for future research that could support developing effective strategies to lessen the aviation sector's environmental and climate impacts.

The challenges in transitioning to sustainable aviation are multifaceted. Although SAF emerges as an immediate solution, as it is compatible with existing aircraft and infrastructure, it requires addressing issues such as limited technological maturity, high costs, feedstock sustainability, competition for resources from other sectors, and lack of financial backing. Hydrogen and electric aircraft face significant hurdles, such as limitations in battery technology, mixed safety perceptions, need for new infrastructure, and lengthy certification process. Operational improvements, such as optimizing flight schedules, can help further but require balancing carbon emission reductions, air quality improvements, and passenger satisfaction. Finally, the rising demand for air travel necessitates finding ways to encourage people to opt for more sustainable options.

Various policy solutions can address these challenges. Strict aircraft emission standards and R&D subsidies can drive innovation in design, pushing manufacturers to develop more environmentally friendly options. Financial incentives, such as grants and

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tax credits, can reduce SAF production and usage costs, and market-based measures, such as CORSIA, can motivate airlines to adopt SAF. Moreover, policies such as incentives for electric GSE can support sustainable airport infrastructure. Investment in alternatives, such as high-speed rail, and policies such as taxing passenger flights can also encourage more sustainable travel choices.

Despite these efforts, many open questions remain. Research is critical for understanding the various impacts of aircraft emissions, the comprehensive air quality and climate benefits offered by SAF, and the nuances of indirect land use changes. It is also vital in assessing the infrastructure and policy needs for advancing SAF, hydrogen, and electric aviation, evaluating the effectiveness of different policies, as well as formulating strategies for the reduction and regulation of non-CO_2 emissions. Additionally, understanding consumer behavior toward sustainable transportation and the effectiveness of policies to change these behaviors is crucial. Finally, developing a globally accepted method for attributing carbon emissions to individual countries remains a challenge, highlighting the need for continued research.

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