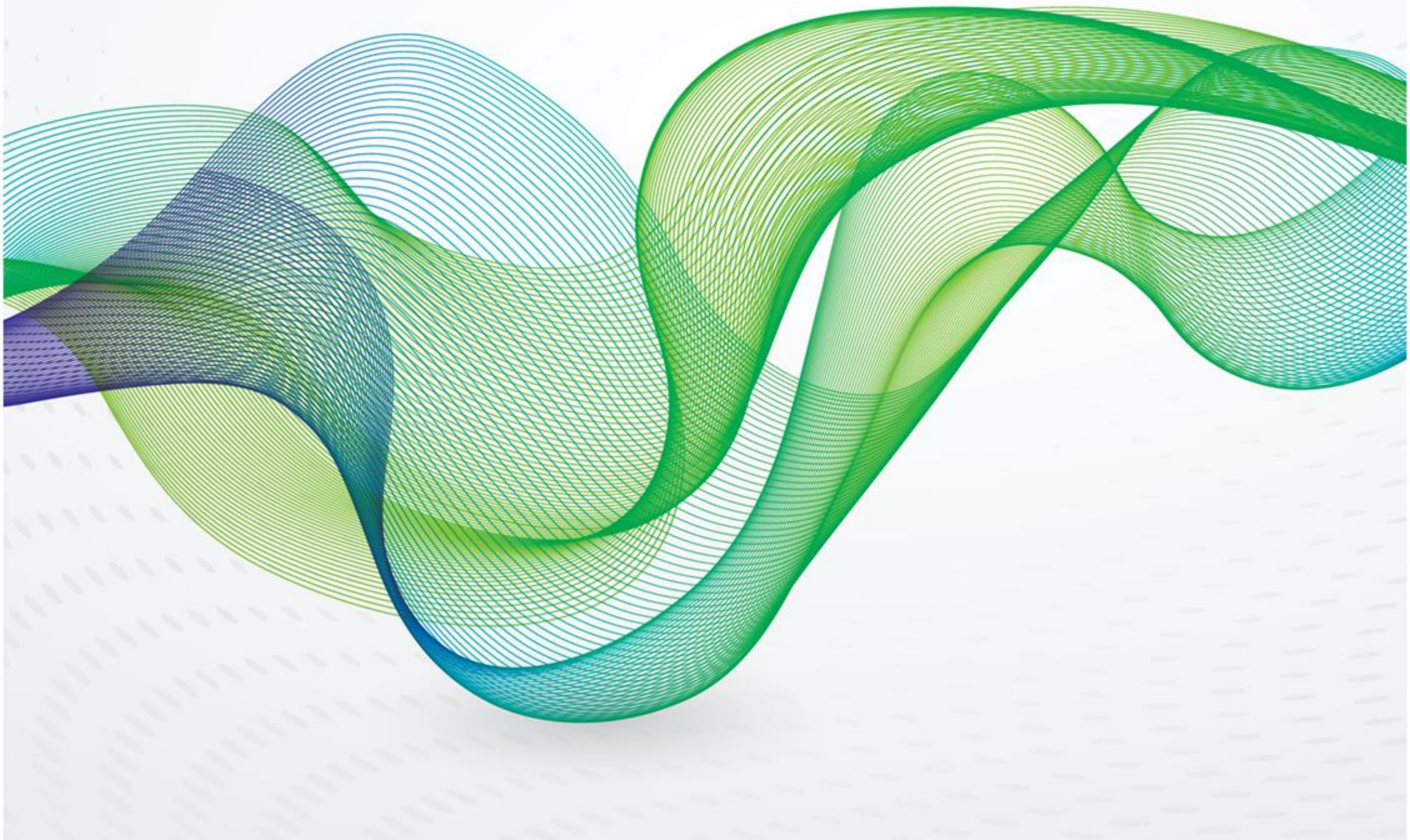
January 2024

Navigating Turbulence:
Hydrogen’s Role in the Decarbonization of the Aviation Sector



OIES Paper: ET28

Abdurahman Alsulaiman, OIES-Aramco Fellow, OIES

ISBN 978-1-78467-226-3

Abstract

This paper offers a comprehensive analysis of the historical evolution and the current state of the aviation industry, with a particular emphasis on the critical need for this sector to decarbonize. It delves into emerging propulsion technologies such as battery electric and hydrogen-based systems, assessing their potential impact on sustainability within the aviation sector. Special attention is devoted to the global regulatory framework, notably carbon offsetting and emission reduction scheme for international aviation, which encapsulates initiatives such as lower carbon aviation fuels and sustainable aviation fuels. Examining the environmental challenges facing aviation, the paper underscores the necessity for a balanced and comprehensive strategy that integrates various approaches to achieve sustainable solutions. By addressing both the historical context and contemporary advances, the paper aims to provide a nuanced understanding of the complexities surrounding aviation's decarbonization journey, acknowledging the industry's strides while recognizing the ongoing challenges in the pursuit of sustainability.

Contents

Figures and Tables

Introduction

In today's aviation landscape, the sector predominantly relies on conventional aviation fuels (represented by Jet A, Jet A1, Jet B, JP 5, JP 8, and Avgas), the majority of which are Jet A and Jet A-1, which are derived from crude oil.[1][2] These fuels have long held sway as the industry's go-to choice, thanks to their well-established compatibility with existing aircraft engines and their consistent performance in a wide array of conditions. Nevertheless, against the backdrop of the global endeavour to combat anthropogenic emissions and address the urgent challenge of climate change, the aviation industry finds itself facing formidable turbulence on its path towards decarbonization. Encouragingly, a spectrum of technologies is poised to usher in a transformative era of sustainable aviation practices.

In the short to medium-term, solutions such as drop-in fuels, capable of seamlessly substituting for traditional aviation fuels while concurrently curbing fossil-based carbon emissions, offer promising avenues for adoption. Yet, when looking further ahead for long-term solutions, advanced propulsion systems driven by hydrogen and electricity emerge as game-changing alternatives that hold significant potential for revolutionizing aviation sustainability.

When considering the industry's decarbonization pathways, hydrogen is seen as a focal point in the industry's path towards decarbonization. Interestingly, the use of hydrogen up to 2050 is likely to be mainly concentrated within its potential use in scaling up production of Sustainable Aviation Fuels (SAFs).[3][4][5] Indeed, SAFs have the potential to significantly reduce the aviation industry's fossil-based carbon footprint, which accounted for 2 per cent of global energy-related CO_2 emissions in 2022, about 80 per cent of its pre-Covid-19 pandemic levels.[6] Nevertheless, SAFs widespread adoption depends on addressing a plethora of technological, infrastructure, and regulatory related challenges.

This paper aims to address a series of key objectives. It begins with a comprehensive examination of the historical and current state of the aviation sector. Subsequently, the report delves into strategies for decarbonizing the aviation sector's fuel consumption, encompassing both short-term and long-term solutions. Another critical objective is to evaluate national and international policies regarding SAFs and provide projections for their production.

1. Historical and current aviation

For centuries, the dream of taking to the skies remained tethered by a single missing element: a means of propulsion. It wasn't until the dawn of the 20th century that the aviation industry truly took off, with the advent of the internal combustion engine. This compact and portable power source defied gravity's grasp and laid the foundation for humanity's soaring journey into the skies.

As aviation's wings unfurled, early aircraft engines borrowed their inspiration from the automotive realm, relying on the same fuels. Yet, the quest for increased power led to the development of specialized engines and aviation fuels, propelling the aviation sector forward. In the 1940s, the turbine engine emerged as the answer to the ceaseless quest for more power, eventually giving rise to specialized aviation turbine fuels.[1]

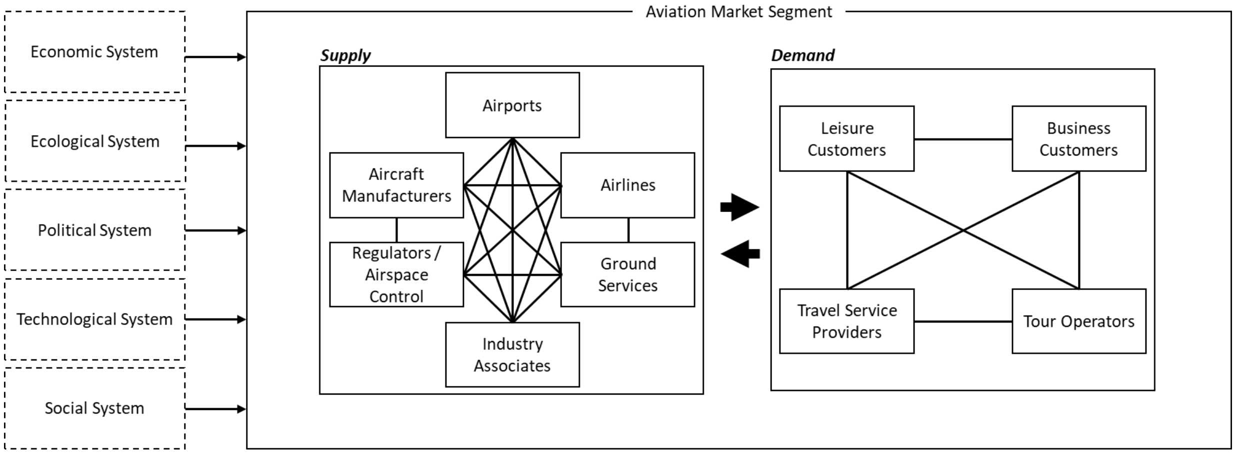
Nevertheless, before delving into today's aviation energy consumption and, consequently, its environmental impact, it is essential to first identify and examine the various stakeholders within the aviation industry. By understanding their respective roles, we can better comprehend the intricate and multifaceted nature of the sector when considering the available options for achieving decarbonization.

In Figure 1, we gain valuable insight into the complex structure of the aviation sector, an industry shaped by an intricate interplay of economic, ecological, political, technological, and social systems. This multifaceted sector encompasses both the supply and demand sides, with numerous stakeholders playing interconnected roles and exerting mutual influence on each other.

---

1 Chevron. (2007). https://www.chevron.com/-/media/chevron/operations/documents/aviation-tech-review.pdf
2 Davidson, C., Newes, E., Schwab, A., and Vimmerstedt, L. (2014). https://www.nrel.gov/docs/fy14osti/60254.pdf
3 IATA. (2021). https://www.iata.org/en/programs/environment/sustainable-aviation-fuels/
4 ICAO. (2022a). https://www.icao.int/environmental-protection/LTAG/Pages/LTAGreport.aspx
5 SkyNRG. (2023). https://skynrg.com/safmo2023/
6 IATA. (2023a). https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/fact_sheet_on_climate_change.pdf

Figure 1: The different stakeholders of the aviation market sector



Source: Adapted from [7]

On the supply side, we find airports as crucial nodes in the aviation ecosystem, serving as more than just points of origin and destination; they are hubs for logistical operations. Airlines, on the other hand, constitute the backbone of the industry, operating fleets of aircraft and making decisions that significantly impact competitiveness and sustainability, such as route planning and pricing structures. Ground services encompass critical activities like baggage handling, passenger boarding, and aircraft servicing, ensuring the smooth operation of flights. Industry associates, including aircraft component suppliers and technology providers, contribute to the industry's efficiency and innovation. Meanwhile, regulators and airspace control entities oversee safety, security, and airspace management, enforcing regulations and upholding international agreements. Aircraft manufacturers play a pivotal role in shaping aviation through innovations in aircraft design and propulsion systems.

On the demand side, leisure customers form a substantial portion of the aviation industry's customer base, with preferences driven by factors like cost, convenience, and destination choices, influenced by economic conditions and societal trends. Business customers, including corporate executives and professionals, have specific travel needs related to schedules and destinations, affecting demand for premium services and preferred routes. Travel service providers, such as travel agencies and online booking platforms, facilitate travel arrangements, offering packages and vital information to customers. Tour operators design and sell vacation packages, collaborating closely with airlines and other travel providers to create comprehensive travel experiences.

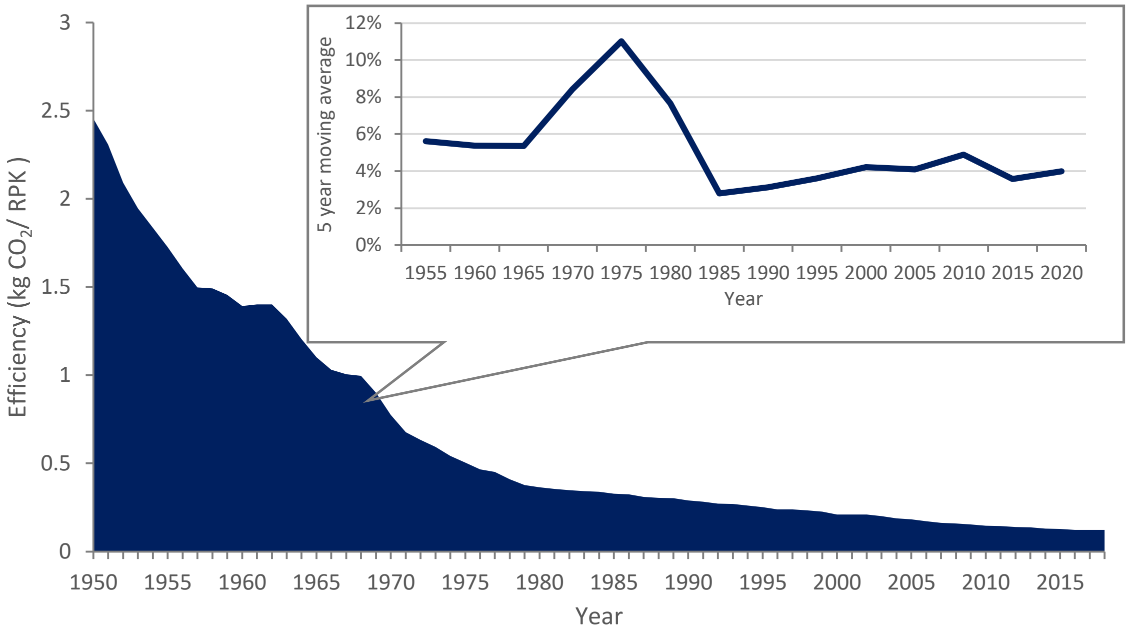
The intricate interplay between supply and demand-side stakeholders characterizes the commercial aviation market. Shifts in passenger preferences, economic conditions, and technological innovations can prompt responses and adaptations from supply-side stakeholders. Conversely, innovations in aircraft design, safety regulations, and airport infrastructure can shape passenger experiences and influence travel choices. Nevertheless, despite its intricate and sometimes delicate nature, aviation has transcended novelty over the past century to become an indispensable pillar of modern society, enabling the swift global movement of people and goods. At the heart of this journey lies the reliance on petroleum fuels, a choice made for their undeniable technical advantages, including higher energy density, ease of handling, and widespread availability among liquid fuels.[1]

Moreover, the aviation industry segment has seen significant advancements in engine technology and aircraft design, leading to the ability to accommodate more passengers and goods transported within the same footprint. These developments have not only enhanced the industry's overall efficiency but can also be argued to have led to the avoidance of a notable increase in emissions, as seen in Figure 2. Nevertheless, despite these significant technical advancements and ongoing efforts to reduce emissions within the aviation sector, a prominent challenge has emerged. The rapid growth of aviation, surpassing efficiency improvements, has resulted in a considerable increase in emissions, as shown in Figure 4, a topic we will delve into later in this section.

---

[7] Wittmer, A., Bieger, T., and Müller, R. (2021). Aviation Systems: Management of the integrated aviation value chain. Cham, Switzerland: Springer.

Figure 2: Aviation transport efficiency from 1950 to 2018



Source: Author's analysis of data from [9].

Note: RPK stands for revenue passenger kilometer.

Here, it is essential to clarify the value in Revenue Passenger Kilometers (RPK), a crucial metric in the aviation industry. RPK measures the total number of kilometers traveled by all paying passengers on a particular flight or within a specified timeframe.[8] This metric is fundamental when evaluating the aviation sector's environmental impact as it accounts for both the number of passengers transported and the distance traveled. Therefore, when comparing RPK to CO_2 emissions, we gain a comprehensive understanding of the industry's environmental efficiency. RPK considers factors such as passenger occupancy and the total distance flown, allowing us to assess how effectively the aviation sector is minimizing its carbon footprint while accommodating the growing demand for air travel. Thus, data in Figure 2 reveals a noteworthy trend where fuel usage and consequently CO_2 emissions have experienced relatively slower growth compared to RPK.

The trend seen in Figure 2 underscores the gains achieved in aircraft efficiency, which have been driven by advancements in technology, the introduction of larger average aircraft sizes, and improved passenger load factors. Indeed, over the decades, aviation transport efficiency has exhibited a remarkable transformation, progressing from over 2000 grams of CO_2 per RPK in the 1950s to a significantly reduced 125 grams of CO_2 per RPK in 2018.[9]

Furthermore, when examining the moving average depicted in Figure 2, a noticeable surge in efficiency improvement becomes evident around the mid-1970s. This notable improvement can be attributed to the introduction of the first modern twin-aisle aircraft, namely the Boeing 747-100. This aircraft, which commenced operation in 1969, and its successor, the 747-200 which began service in 1971, stood out as the largest and most fuel-efficient aircraft models delivered between 1965 and 1975. In 1970, the Boeing 747-100 alone accounted for 39 per cent of all aircraft deliveries in that year, and when combined with the Boeing 747-200 in 1971, they constituted 36 per cent of the market share.[10] The significant size of these aircraft, along with the implementation of the initial High Bypass Ratio (HBR) turbofan engines in the early 747 models, played a crucial role in achieving a substantial improvement in RPK efficiency owing to both

---

8 ICAO. (2020). https://www.icao.int/sustainability/Documents/Post-COVID-19%20forecasts%20scenarios%20tables.pdf

9 Lee, D. S et al. (2020). 'The contribution of Global Aviation to anthropogenic climate forcing for 2000 to 2018'. https://www.sciencedirect.com/science/article/pii/S1352231020305689?ref=pdf_download&fr=RR-2&rr=812f2d52899b4be2

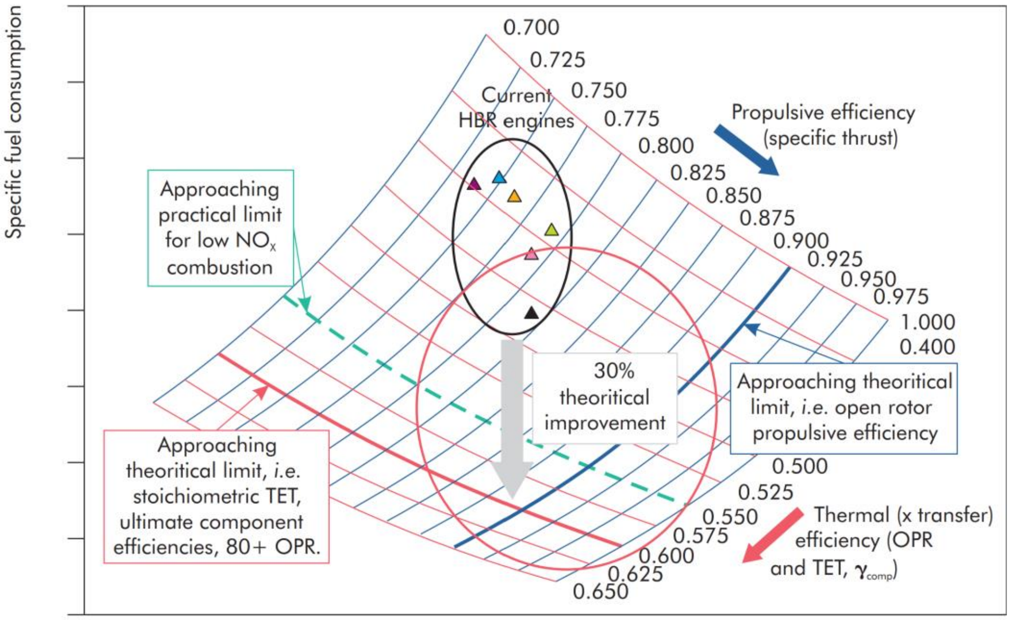
10 Kharina, A. and Rutherford, D. (2015). 'Fuel efficiency trends for new commercial jet aircraft: 1960 to 2014'. https://theicct.org/sites/default/files/publications/ICCT_Aircraft-FE-Trends_20150902.pdf

fuel efficiency and a remarkable increase in passenger carrying capacity. In fact, as seen in Figure 2, we have not seen efficiency gains of such magnitude since the introduction of HBR turbofan engines.

When considering the levels of possible remaining efficiency gain with HBR turbofan engines, we are fast approaching the wall of theoretical efficiency. In recent decades, there has been significant progress in enhancing the fuel efficiency of modern jet engines. Engine design efforts have been twofold: firstly, to enhance propulsion efficiency, and secondly, to increase thermal efficiency, while concurrently addressing issues such as noise reduction and the mitigation of Nitrogen Oxides (NO_X) emissions. Efforts aimed at improving thermal efficiency have concentrated on achieving higher temperatures and pressures, with notable contributions arising from advancements in compressor blade aerodynamics, novel materials, and specialized coatings. This focus yielded substantial results from the 1970s to the early 2000s, leading to a remarkable 35 per cent reduction in fuel consumption and nearly eliminating smoke emissions. However, it is important to note that the pursuit of higher temperatures and pressures in engine design had an unintended consequence: an increase in NO_X emissions.[11] While it might seem counterintuitive that more efficient engines could produce higher NO_X emissions, this phenomenon can be attributed to the elevated temperature and pressure levels, particularly in the presence of atmospheric nitrogen and oxygen. To counteract this environmental impact, engines are currently being developed with innovative features such as water injection systems, intercooling, and chilled air coolers. While these measures hold promise for reducing NO_X emissions, they may come at the expense of efficiency.

In theory, there is potential for a further 30 per cent improvement in fuel consumption; however, practical limitations suggest that, without the introduction of groundbreaking low-NO_X technologies, engines may realistically achieve only an additional 20 to 25 per cent reduction while simultaneously meeting anticipated future NO_X emissions standards. The challenge is clearly illustrated in Figure 3, which schematically portrays the difficulty of concurrently shifting engines towards lower fuel consumption, greater propulsion efficiency, and reduced NO_X emissions.[11]

Figure 3: Fuel consumption map for HBR turbo-jet engines



Source: Adapted from IEA [11]

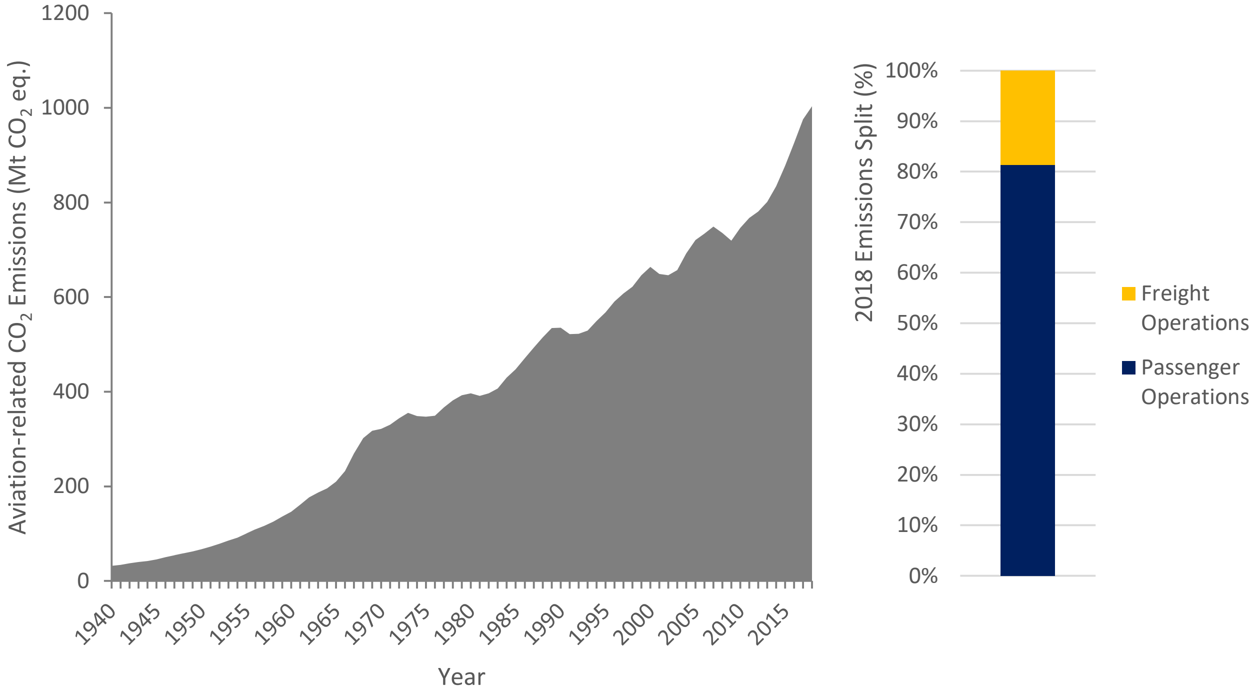
From a technical perspective, striving for the last few percentage points of efficiency is an admirable goal. However, it becomes more complex when we consider the broader context of achieving carbon neutrality by 2050. Even if we achieve the upper limits of efficiency, some of the aircraft produced in the next few years might still be operational by 2050 and without a technological breakthrough in engine efficiency, this reality leads us to a fundamental question regarding the root cause of emissions – the fuel itself. While

[11] IEA. (2009). https://iea.blob.core.windows.net/assets/34816408-681f-4dbb-9a1c-8bf787bf8ad3/transport2009.pdf

enhancing engine efficiency remains a crucial step in reducing emissions, addressing the fuel aspect of the aviation industry also becomes imperative to fully align with the goal of carbon neutrality.

Considering efficiency alone is impossible without acknowledging the rapid expansion of the aviation industry, primarily driven by factors such as increased affordability, economic growth, and globalization.[12] This expansion leads to a substantial rise in emissions, as shown in Figure 4. Even with efficiency gains, the continued growth of the industry has led to a relentless increase in emissions.

Figure 4: Global CO_2 emissions related to aviation activates from 1940 to 2018



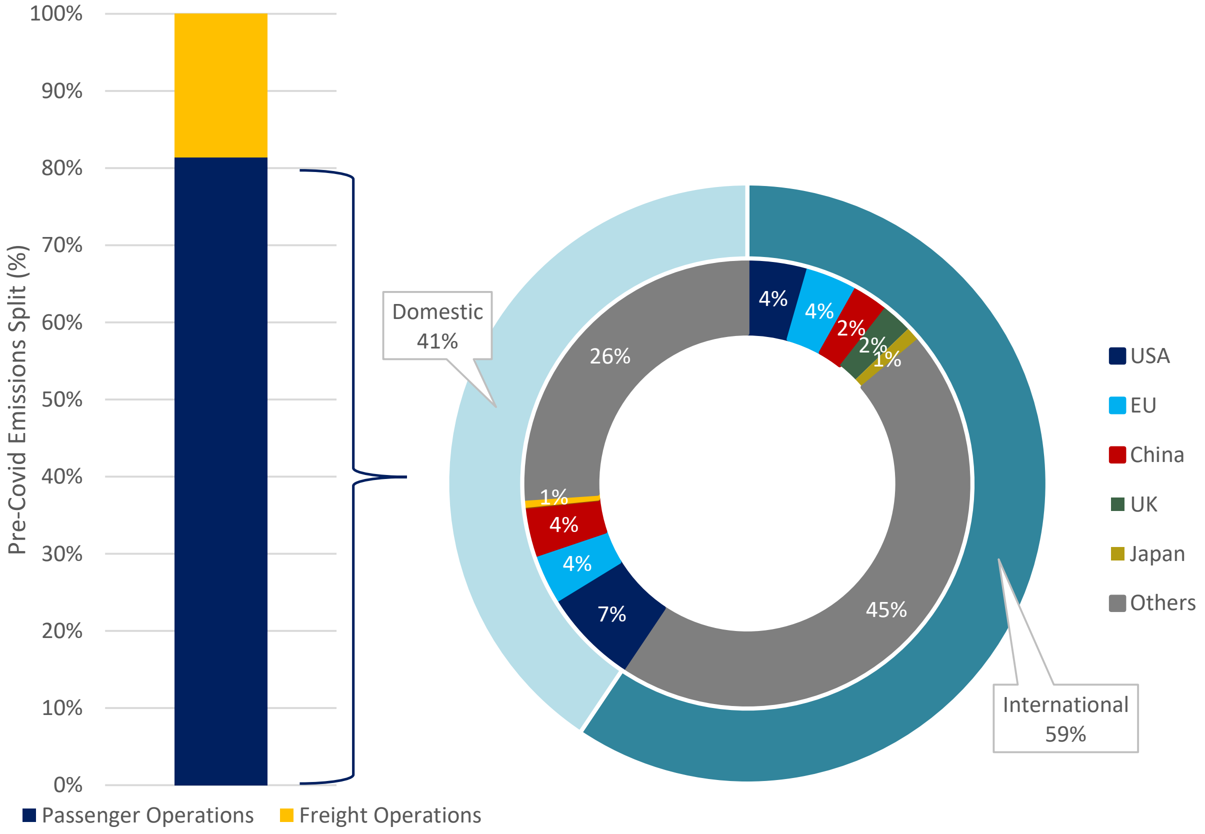
Source: Author's analysis of data from [9], and [13]

Considering the data presented in Figure 5, which reveals that passenger-transport activities contribute to over 80 per cent of total CO_2 emissions within the aviation sector (excluding military operations), it becomes evident that prioritizing the passenger segment is essential when crafting emissions reduction strategies. However, this presents a two-fold challenge. On one side, there is a recognition of the need to focus on emissions reduction in passenger air travel. Yet, on the other side, there is the challenge of achieving this goal while ensuring that major stakeholders in the passenger aviation industry can transition fairly and sustainably without significant disruption to their operations, and by extension, to the passengers themselves. Consequently, it is imperative for decision makers and regulators to adopt an informed and well-studied approach that is intricately linked with a sustainable transition.

[12] Esqué, A., Fuchs, G., and Riedel, R. (2022). 'Fuel efficiency : Why airlines need to switch to more ambitious measures.' https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/future-air-mobility-blog/fuel-efficiency-why-airlines-need-to-switch-to-more-ambitious-measures

[13] Graver, B., Zhang, K., and Rutherford, D. (2022). 'CO2 emissions from commercial aviation, 2018.' https://theicct.org/publication/co2-emissions-from-commercial-aviation-2018/

Figure 5: Global CO_2 emissions split in different aviation activates (left) and countries (right) in 2018



Source: Author's analysis of data from [9], and [13]

Looking at the global distribution of emissions in passenger aviation, partially shown Figure 5, it is observed that developed economies collectively account for approximately 50 per cent of international aviation emissions and 60 per cent of domestic aviation emissions. However, beyond the major contributors such as the United States, European Union, China, United Kingdom, and Japan, the variance in emissions among the remaining nations is hypothesized to follow a GDP per capita distribution.[13] This underscores the international nature of the issue at hand, necessitating an international solution. Nevertheless, such a solution should consider the principles of equitable and just distribution of responsibilities and contributions among nations.

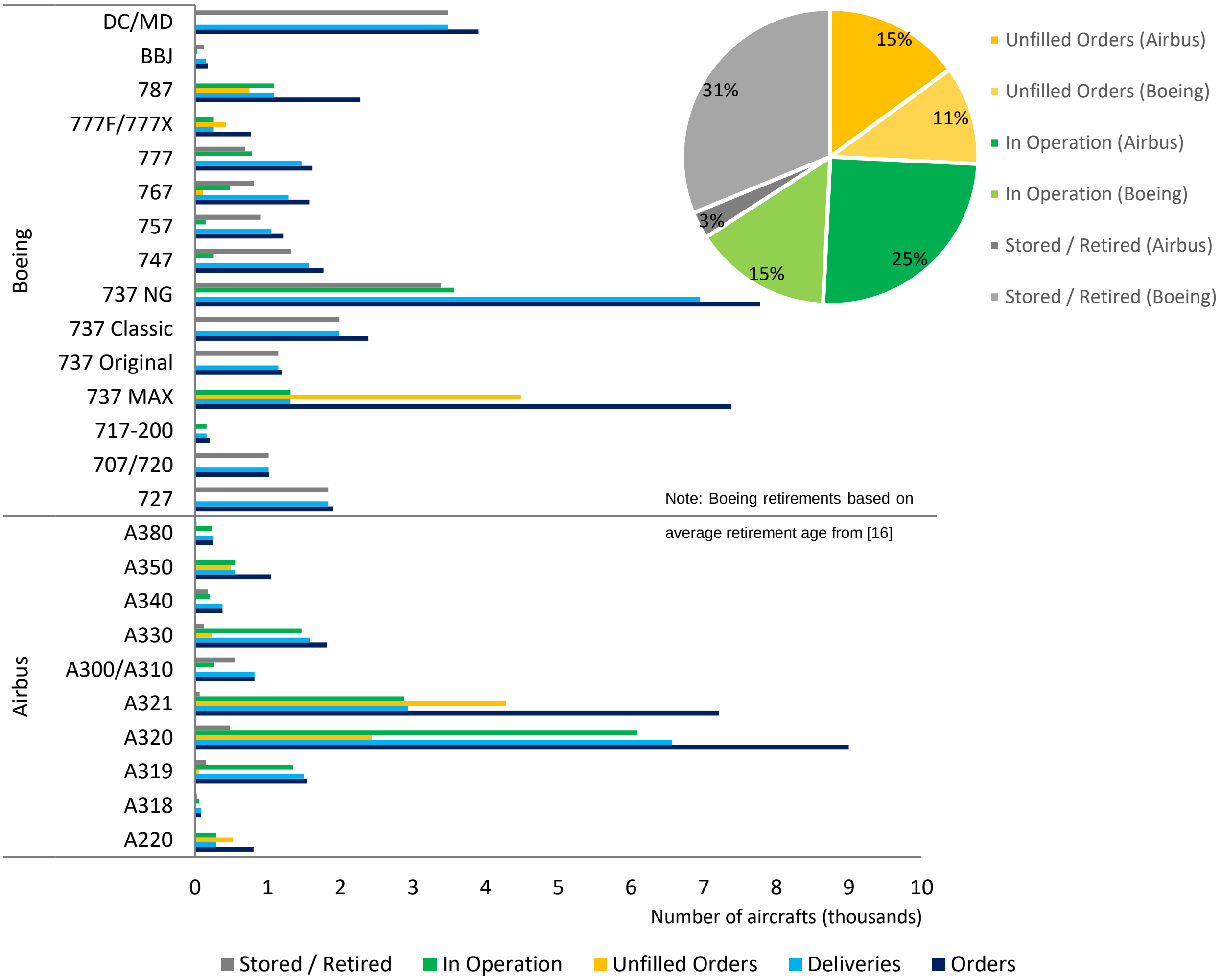
Comparatively, when contrasting the aviation sector with other modes of transportation such as rail or road, a noteworthy trend is reported in the form of emissions from the aviation sector surging at a faster rate.[14] Even following the sharp reduction in aviation demand triggered by the COVID-19 pandemic in 2020, it appears that by 2024, sector emissions would reach pre-COVID-19 levels.[15] However, while some transport sectors, such as rail and road, have made progress in commercializing decarbonized solutions, this is not the case in aviation. This underscores the importance of putting the surge in aviation emissions into context and using it as a compelling push towards the commercialization of decarbonized solutions in the aviation sector.

Moreover, as mentioned earlier, some aircraft made with today's technology could still be operational by 2050. An analysis of today's active fleets from the two largest aircraft producers, Boeing and Airbus, as seen in Figure 6, reveals the current distribution of aircraft models. The significance of this analysis lies in the fact

[14] IEA. (2023). https://www.iea.org/energy-system/transport/aviation
[15] IATA. (2023b). 'Global outlook for air transport highly resilient, less robust.' https://www.iata.org/en/iata-repository/publications/economic-reports/global-outlook-for-air-transport----june-2023/

that some of the aircraft models included are more than 30 years old, and yet they continue to operate today, with some even reaching the age of 40 years.[16] As a point of reference, it is noteworthy that around 50 per cent of airworthy aircraft in 2015 were already 28 or more years into their service life, as depicted in Figure 7. Still, the aircraft industry commonly practices retrofitting and upgrading of older models. However, unless a robust global carbon pricing mechanism is implemented for aviation, it becomes challenging to envision operators of 30-year-old aircraft willingly undertaking comprehensive overhauls of an aircraft's fuel and engine systems. Consequently, it remains a distinct possibility that aircraft models produced in the 2020s may continue to operate with engines running on today's emissions standards by 2050, assuming a 'business as usual' scenario and the effects of grandfathering; where provisions are made to allow for older standards to be accepted for older aircraft models.

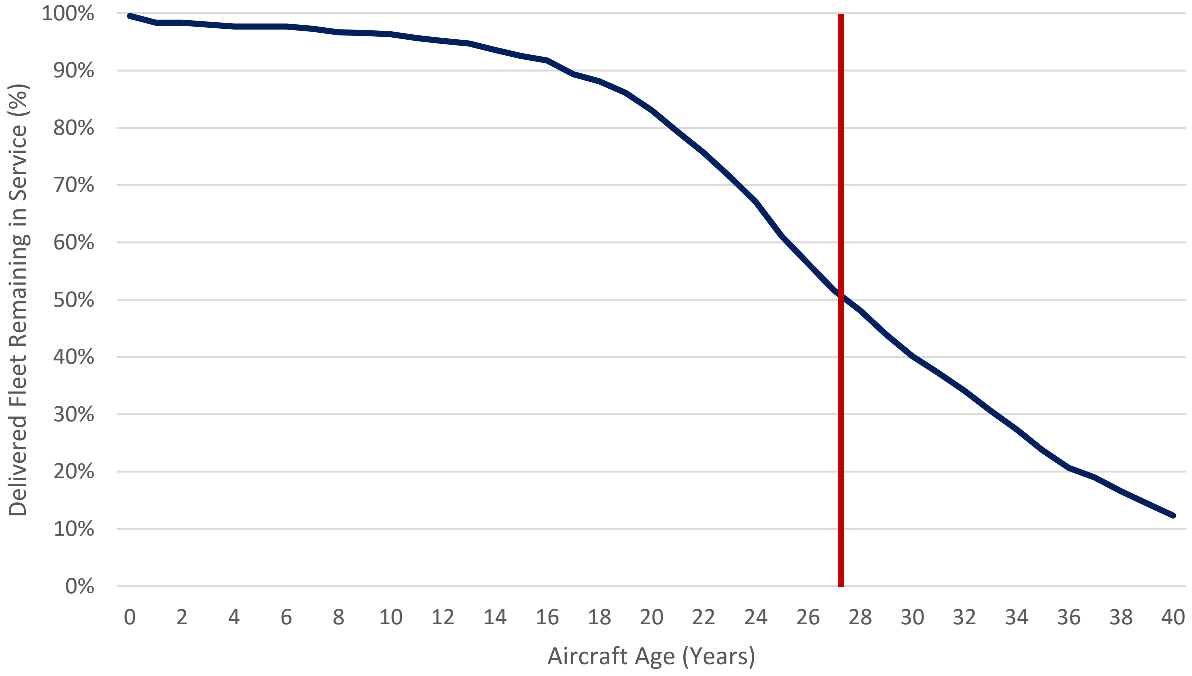
Figure 6: Current status of Airbus and Boeing fleets



Source: Analysis of data from [16], [17], and [18]

[16] Forsberg, D. (2015). 'Aircraft Retirement and Storage Trends.' https://aviation.report/Resources/Whitepapers/c7ca1e8f-fd11-4a96-9500-85609082abf7_whitepaper%201.pdf
[17] Airbus. (2023). https://www.airbus.com/en/products-services/commercial-aircraft/market/orders-and-deliveries
[18] Boeing. (2023). https://www.boeing.com/commercial/#/orders-deliveries

Figure 7: Average age of commercial aircraft remaining in service



Source: Analysis of data from [16]

The pursuit of decarbonizing aviation reveals a multifaceted challenge, as underscored by the analysis presented earlier. To achieve meaningful decarbonization in aviation, the fundamental source of emissions—the fuel—must be addressed. Two key methods come to the forefront for addressing this challenge. Firstly, decarbonizing the fuel itself offers a solution without requiring a structural change in how planes operate and fly today. Secondly, by drawing a parallel with the introduction of the HBR-turbofan engine in the 1970s, innovation in the means of propulsion could pave the way for aviation to shift from carbon-based fuels to hydrogen combustion or even entirely non-combustion methods like electricity. Such innovations would fundamentally reshape the aviation fuel chain.

2. Aviation decarbonization methods

In this section, two distinct approaches to achieving aviation decarbonization will be discussed. The first approach focuses on addressing the fuel and means of propulsion through the use of electricity and hydrogen to provide the required thrust for aircraft. The second approach specifically aims at the fuel, either by reducing the upstream intensity or by chemically synthesising jet fuel using renewable resources. This second approach is limited to what is currently accepted within the definitions set within the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), an International Civil Aviation Organization (ICAO) scheme directed at mitigating carbon emissions in international aviation.

2.1 New propulsion technology

2.1.1 Battery electric propulsion

Battery-electric systems have changed the ground transportation industry and various other markets, contributing to significant advancements in operational capabilities and energy storage properties. At first glance, when considering battery-based systems as a sustainable energy source for aviation, their merits become apparent. Unlike other energy carriers, battery systems used for aircraft propulsion do not emit direct emissions during operation.[19][20]

Additionally, battery-electric systems offer higher end-to-end drivetrain efficiencies compared to traditional jet engines and hydrogen-based propulsion. In a study, from a well-to-wake approach, it was calculated that for every 1 MJ at an aircraft's fan, it would require ~1.3 MJ from a battery-electric system, ~4.1 MJ for a hydrogen fuel-cell system, ~5.2 MJ from a hydrogen combustion system, and ~5.7 MJ from an SAF based system.[21]

Indeed, battery electric systems provide higher system efficiencies. Yet they also pose a multitude of issues for commercial aviation. The primary challenge lies in their relatively low specific energy. In the foreseeable future, these systems are primarily suitable for light-payload and limited-range aircraft. Nevertheless, the aviation industry has embraced battery-electric systems through the widespread adoption of more-electric aircraft systems, which substitute engine-bleed and hydraulic actuation systems with electrical counterparts to enhance overall system efficiency and reduce weight. This shift toward electrification has also sparked numerous studies exploring fully electric and hybrid-electric aircraft configurations. However, it is important to note that these studies reveal that fully electric battery energy storage systems for commercial transport aircraft are not feasible in the near to mid-term, with lightly hybridized configurations showing only modest fuel efficiency improvements.[22]

The insufficient specific energy of battery systems represents the primary technical barrier preventing their use as a primary energy carrier for aircraft. Additionally, batteries exhibit other material characteristics that pose challenges for integration at the power and energy levels required for aviation. Many secondary batteries are susceptible to thermal runaway events, with the likelihood of such events dependent on cell chemistry, configuration, charge, and pack integration. Therefore, ensuring the reliability and safety of batteries in aircraft remains a recognized challenge, with incidents of fires reported for several battery-electric aircraft prototypes and early commercial flights of the Boeing 787 aircraft.[22]

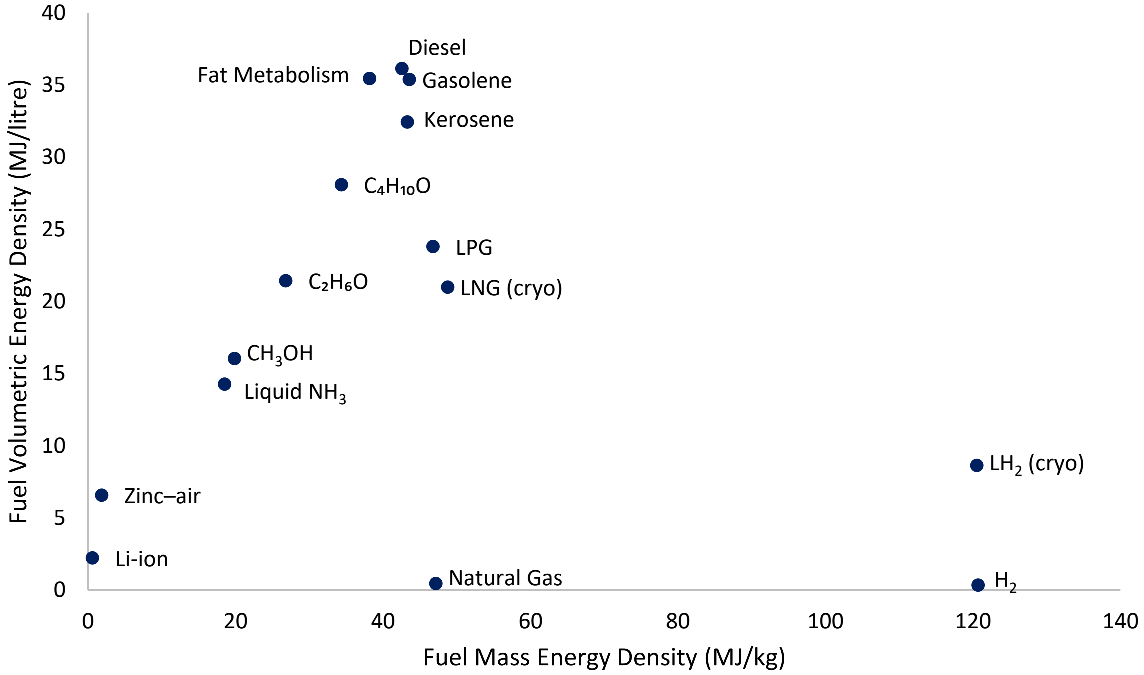
As mentioned earlier, battery-electric power systems do not produce direct emissions, shifting the environmental sustainability focus to the energy production pathways of the electrical grid, and the energy used and emissions released throughout the battery manufacturing value chain. Certainly, reducing emissions with the adoption of battery-electric aircraft depends heavily on the increased development of renewable energy power sources and sustainable battery manufacturing value chains. Within the area of renewable power, in 2022, renewables constituted roughly 14 per cent of the global electricity grid. Projections suggest that, at the lower end, renewables are expected to account for approximately 60 per cent of power generation by 2050, and potentially reaching as high as 80 per cent. If we include low-carbon sources like nuclear and hydro, the figure could approach 100 per cent.[23] Nevertheless. These supply projections are not sized for the potential demand of a fully electrified aviation sector.

Moreover, an area which has been stated as advantageous for battery-powered aircraft is their lower and stable cost per unit energy compared to traditional jet fuel, which is more volatile. However, it is essential to consider that battery-electric systems would incur significantly higher costs per unit RPK due to their greater weight. Perhaps another seemingly positive characteristic in batteries is their sharp decrease in price over the years, with the capital expense of batteries decreasing significantly over the past decade, with electric vehicle battery packs dropping from $732/kWh in 2013 to $151/kWh in 2022 (US$ 2022 values used).[22] Yet, in an industry which optimizes for weight and volume, the mass and volumetric energy densities of batteries (see bottom left side of Figure 8) pose a large technical downgrade, even when compared to gaseous hydrogen (see bottom right), as can be seen in Figure 8.

---

19 Bills, A. et al. (2020). 'Performance Metrics Required of Next-Generation Batteries to Electrify Commercial Aircraft.' https://pubs.acs.org/doi/10.1021/acsenergylett.9b02574
20 Brelje, B., and Martins, J. (2019). 'Electric, hybrid, and turboelectric fixed-wing aircraft : A review of concepts, models, and design approaches.' https://www.sciencedirect.com/science/article/pii/S0376042118300356
21 Harris, J., Danicourt, J., Papania, and Kim, A. (2022). 'Will Plans to Decarbonize the Aviation Industry Fly?' https://www.bain.com/insights/will-plans-to-decarbonize-the-aviation-industry-fly/
22 Ansell, P. (2023). 'Review of sustainable energy carriers for aviation: Benefits, challenges, and future viability.' https://www.sciencedirect.com/science/article/pii/S0376042123000350#bb267
23 IEA. (2023). 'World Energy Outlook 2023' https://www.iea.org/reports/world-energy-outlook-2023

Figure 8: Mass and volume energy densities of different energy carriers



Source: Adapted from [24]

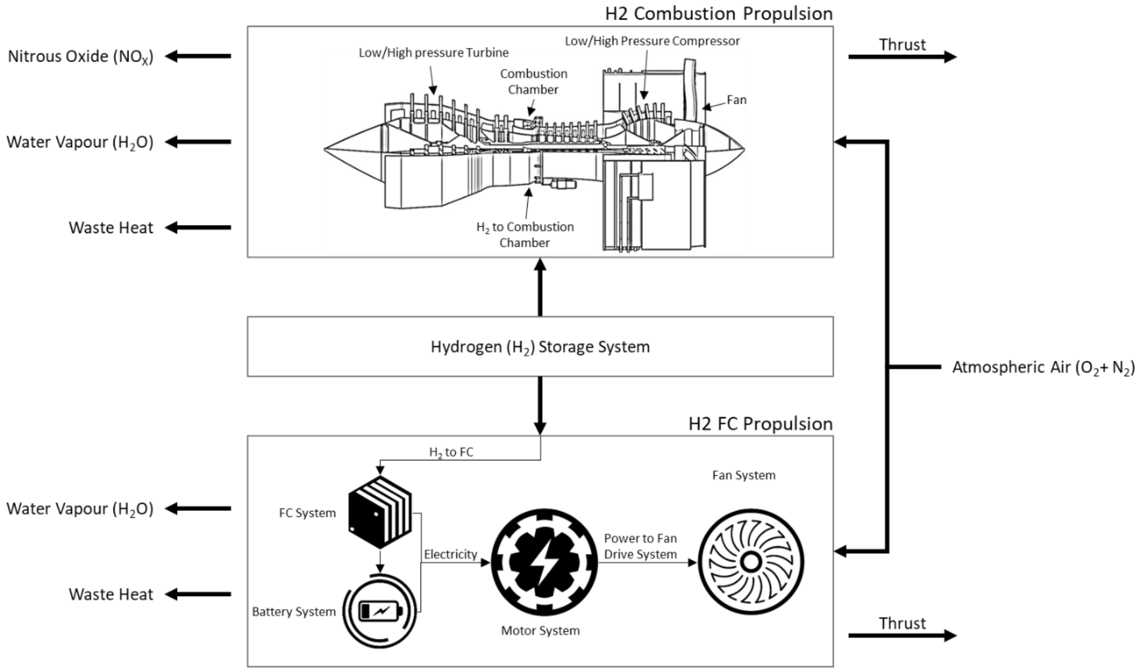
Furthermore, the sustainability impacts of battery-electric power systems are intricately tied to developments in the electrical grid, primary resource production, land requirements, and the adverse effects of mining critical minerals. When we focus on critical minerals, such as those used in battery packs for electric vehicles, mining practices for raw materials like cobalt, lithium, nickel, manganese, and graphite raise significant social sustainability concerns. These materials are associated with issues like over-extraction, endangering local ecosystems, increased local and global emissions, child labour, exposure to occupational toxins, forced labour practices, soil erosion, and the perpetuation of poverty within vulnerable communities.[22][25][26] Notably, this consideration becomes even more critical in the context of aviation's scale, where questions emerge, including the implications of battery capacity loss and the feasibility of battery replacements in aviation, which may occur every few years.

[24] Rao, A., and Yin, F. (n.d.). 'A Hybrid Engine concept for Multi-fuel Blended Wing Body.' https://www.researchgate.net/publication/270759537_A_Hybrid_Engine_Concept_for_Multi-fuel_Blended_Wing_Body
[25] Delevingne, L., Glazener, W., Grégoir, L., and Henderson, K. (2020). 'Climate risk and decarbonization: What every mining CEO needs to know.' https://www.mckinsey.com/capabilities/sustainability/our-insights/climate-risk-and-decarbonization-what-every-mining-ceo-needs-to-know
[26] Ramdoo, I. (2023). 'Mining and Climate Change: Risks, responsibilities, and solutions.' https://www.igfmining.org/mining-climate-change-risks-responsibilities-solutions/#:~:text=Effects%20are%20being%20felt%20through,and%20water%2C%20among%20other%20things

2.1.2 Hydrogen-fueled propulsion

Hydrogen can be utilized for aircraft propulsion through two distinct methods: firstly, via hydrogen combustion, and secondly, through the use of fuel cells. A simplified schematic of these methods is depicted in Figure 9.

Figure 9: Possible hydrogen-fuelled propulsion method configurations



Source: Author's analysis of [27]

As illustrated in Figure 9, hydrogen can serve as a direct fuel source for aircraft propulsion through two main techniques. The initial approach involves using it in a manner similar to traditional jet fuel in hydrogen-compatible jet engines. This offers the advantage of complete carbon emissions elimination. In this scenario, the primary exhaust emissions from these jet engines would consist of water vapour (H_2O), NO_X, and residual heat. The second approach represents a novel development in aviation, as it achieves takeoff by utilizing electricity generated from hydrogen-fed fuel cells instead of relying on combustion. This method, along with electric battery-powered flight, marks a significant departure from the conventional means of taking to the skies in the last century. In a fuel cell-powered aircraft, hydrogen is converted into electricity, which, in turn, propels an electric motor and a fan or propeller to generate the required thrust. The main emissions from the fuel cells in this case are primarily H_2O and residual heat.[27]

Before the year 2020, there were only nine publicly accessible initiatives focused on aircraft propelled by hydrogen. Out of these projects, eight utilized fuel cells, while one aimed to harness hydrogen combustion.[Error! Bookmark not defined.] Among these initiatives, only the HY4 project achieved a notable ilestone when it took flight in September 2016. This four-seater aircraft relied on hydrogen fuel cells and employed gaseous hydrogen as its primary fuel source.[28] However, beginning in 2020 and continuing forwards, there has been a discernible surge in the number of projects involving hydrogen-powered aircraft. One of the most significant and ambitious endeavors is Airbus' ZEROe initiative, which has set the goal of introducing the world's first commercial aircraft powered by hydrogen by the year 2035.[29] Furthermore, the team behind the HY4 project achieved another noteworthy accomplishment in September 2023 by conducting the first flight using liquid hydrogen and fuel cells. This transition from gaseous to liquid hydrogen

[27] Thomson, R., Weichenhain, U., and Sachdeva, N. (2020). https://www.rolandberger.com/en/Insights/Publications/Hydrogen-A-future-fuel-for-aviation.html

[28] German Aerospace Center (DLR). (2016). 'Zero-emission air transport – first flight of four-seat passenger aircraft Hy4.' https://www.dlr.de/en/latest/news/2016/20160929_zero-emission-air-transport-first-flight-of-four-seat-passenger-aircraft-hy4_19469

[29] Airbus. (2020). 'ZEROe Towards the world's first hydrogen-powered commercial aircraft.' https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe

effectively doubled the aircraft's range, extending it from 750 kilometers to 1500 kilometers, according to the company's assertions.[30]

In early 2022, following the pandemic, two out of the three leading turbofan engine manufacturers introduced notable advancements in hydrogen-powered technology for commercial aviation. Pratt & Whitney, in February 2022, revealed its selection by the US Department of Energy to develop the innovative hydrogen Steam Injected, Inter-Cooled Turbine Engine (HySIITE). This engine employs liquid hydrogen for combustion and is part of the US Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) program.[31] In the same month, CFM, a collaborative partnership between General Electric and Safran Aircraft Engines, announced their cooperation with Airbus to perform tests on an aircraft engine powered by hydrogen.[32] Furthermore, in November 2022, the remaining major turbofan engine manufacturer, Rolls-Royce, achieved a significant milestone in collaboration with easyJet by successfully converting a Rolls-Royce AE 2100-A regional aircraft engine to operate exclusively on renewable hydrogen.[33]

To summarize the differences and similarities between the two hydrogen propulsion methods, Figure 10 provides a comparative overview of hydrogen-powered fuel cells and combustion.

Figure 10: Analysis of different aviation value-chain components in hydrogen-powered fuel cells and combustion

		Hydrogen fuel cells	Hydrogen combustion
Climate impact	Direct CO_2	-100%	-100%
	Nitrogen Oxides (NO_x)	-100%	-50% to -80%
	Water vapour	+150%	+150%
	Contrails cirrus	-60% to -80%	-30% to -50%
Aircraft design	Compatibility with conventional engines	No compatibility	Some compatibility
	Engine architecture	New propulsion concept	Same propulsion concept
	Aircraft architecture	New fuselage required	New fuselage required
	Electrical systems	New system requirements	Traditional system requirements
	Increased fuel volume compared to kerosene	High for gaseous H_2 Medium for liquid H_2	High for gaseous H_2 Medium for liquid H_2
	Increased fuel and propulsion system mass	High for gaseous H_2 Medium for liquid H_2	High for gaseous H_2 Low for liquid H_2
Aviation supply chain	Complexity	High complexity	Medium complexity
	Infrastructure	High for gaseous H_2 Medium for liquid H_2	High for gaseous H_2 Medium for liquid H_2
Hydrogen source	Fossil–based	Requires carbon capture and storage for H_2 production	Requires carbon capture and storage for H_2 production
	Renewable–based	No requirements	No requirements

Source: Author's analysis of data from [27], [34], and [35]

[30] H2FLY. (2023). 'H2FLY and Partners Complete World's First Piloted Flight of Liquid Hydrogen Powered Electric Aircraft.' https://www.h2fly.de/2023/09/07/h2fly-and-partners-complete-worlds-first-piloted-flight-of-liquid-hydrogen-powered-electric-aircraft/

[31] Pratt & Whitney (2022). 'Pratt & Whitney Awarded Department of Energy Project to Develop Hydrogen Propulsion Technology.' https://www.prattwhitney.com/en/newsroom/news/2022/02/21/pw-awarded-department-of-energy-project-to-develop-hydrogen-propulsion-technology

[32] GE. (2022). 'Hydrogen Takes Flight: Airbus And CFM International To Partner On Hydrogen-Fueled Demonstration.' https://www.ge.com/news/reports/hydrogen-takes-flight-airbus-and-cfm-international-to-partner-on-hydrogen-fueled

[33] RR. (2022). 'Rolls-Royce and easyJet set new world first.' https://www.rolls-royce.com/media/press-releases/2022/28-11-2022-rr-and-easyjet-set-new-aviation-world-first-with-successful-hydrogen-engine-run.aspx?sc_lang=en

[34] EASA. (2022). https://www.easa.europa.eu/en/light/topics/hydrogen-and-its-potential-aviation

[35] FCH JU. (2020). https://www.euractiv.com/wp-content/uploads/sites/2/2020/06/20200507_Hydrogen-Powered-Aviation-report_FINAL-web-ID-8706035.pdf

From Figure 10, in a world that strictly controls carbon emissions, hydrogen-powered aviation could assume a significant role in achieving carbon neutrality. However, it is crucial to highlight two important points.

Firstly, in an industry that's highly regulated and driven by efficiency, it is challenging to imagine a future where both hydrogen-powered and conventional aircraft coexist equally. Airlines, aiming for increased profitability through streamlined operations, may find it impractical to manage two entirely different types of aircraft with distinct propulsion systems. The history of the Aérospatiale/BAC Concorde serves as a pertinent example where innovation was constrained within the aviation industry.

Secondly, the timeframe is of paramount importance, especially in an industry where safety holds the highest priority. It is quite challenging to envision the complete decarbonization of aviation by 2050 solely through the adoption of new aviation propulsion technologies, even if hydrogen-powered planes become a reality as early as 2035, as indicated by Airbus.[36] The widespread adoption of these aircraft and the development of their necessary infrastructure will inevitably take time. Hydrogen-powered flight is unlikely to serve as the primary means to achieving carbon neutrality by the mid-21st century. This accomplishment is more likely to be attributed to SAFs and efficiency enhancements. This perspective aligns with the scenarios outlined in the ICAO Long-Term Aviation Goals (LTAG) report. [37]

2.2 CORSIA

CORSIA represents a significant international initiative directed at mitigating carbon emissions in the aviation sector and actively contributing to global environmental goals. This program not only mandates emissions monitoring and reporting for airlines but also establishes a framework for reducing the sector's carbon footprint and advancing sustainability through the utilization of SAF and Lower Carbon Aviation Fuels (LCAF).[38] The definitions of SAF and LCAF in this section adhere to CORSIA's criteria, ensuring alignment with the preferences of the majority of ICAO's member states, which are part of CORSIA and represent more than 75 per cent of international aviation emissions in 2019.

2.2.1 Lower carbon aviation fuel

A LCAF, as outlined in Annex 16 Volume IV,[4][39] is a fossil-based aviation fuel that adheres to the CORSIA Sustainability Criteria, thereby playing a significant role in mitigating the overall greenhouse gas (GHG) lifecycle emissions associated with the aviation industry. To achieve certification as a CORSIA eligible fuel, an LCAF must meet stringent criteria, including the prerequisite of a 10 per cent reduction in lifecycle emissions compared to the conventional aviation fuel baseline of 89 gCO2e/MJ. LCAF encompasses a diverse array of innovative technologies and processes aimed at curbing GHG emissions in the production phase of aviation fuel. These include measures such as enhancing energy conservation practices, reducing methane emissions through equipment upgrades and improved production techniques, employing flare gas recovery systems for emissions reduction, monitoring and controlling venting operations, and leveraging advanced technologies like optical gas imaging and satellite imagery for fugitive emissions detection. Moreover, LCAF embraces Carbon Capture and Storage (CCS) to collect and store CO_2 emissions generated during fossil fuel production, renewable electricity sources for reducing emissions related to energy consumption, and the production of hydrogen with lower carbon intensity, be it 'blue hydrogen' with CCS or 'green hydrogen' generated using renewable electricity. The use of new crude oils with improved characteristics and the production of SAF through co-processing in existing refinery infrastructure are also integral components of LCAF strategies.[40] Figure 11 shows the possible way in which LCAF can reduce its lifecycle emissions, according to ICAO statistics.

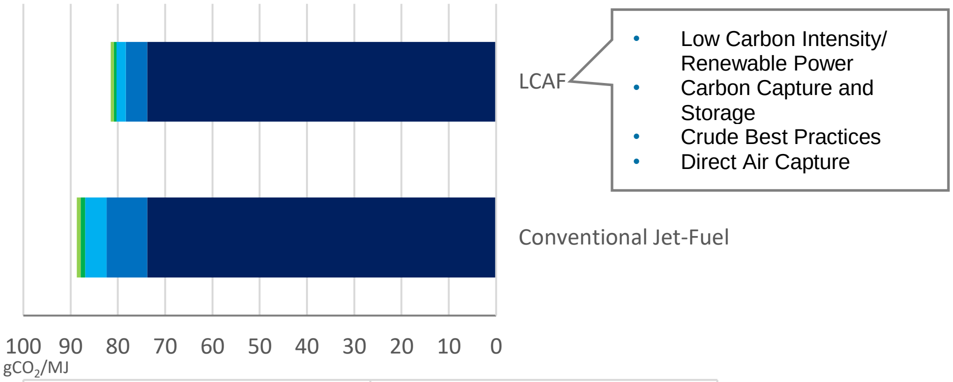
Moreover, it is worth noting that LCAF should not be viewed in isolation; it presents significant opportunities when considered alongside SAF as both LCAF and SAF can be processed and blended within refinery facilities, making refineries a pivotal player in achieving sustainability goals in aviation. Refineries, being the crucial link between fuel supply and demand, serve as potential optimal locations for large-scale and

---

36 Airbus. (2020). https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe
37 ICAO. (2023). 'Long term global aspirational goal (LTAG) for international aviation.' https://www.icao.int/environmental-protection/Pages/LTAG.aspx
38 ICAO. (2018). https://www.icao.int/environmental-protection/CORSIA/Pages/SARPs-Annex-16-Volume-IV.aspx
39 ICAO. (2023a). https://www.icao.int/environmental-protection/pages/SAF.aspx
40 ICAO. (2023b). https://www.icao.int/environmental-protection/Documents/LCAF/LCAF%20Technologies%20Update%20-%20April%202023.pdf

sustainable blending of these low-carbon fuels. Refineries also play a pivotal role in processing LCAF and SAF. In the pursuit of optimizing their emissions reduction strategies, refineries can strategically consider both LCAF and SAF, allowing them to economically meet emissions intensity targets. While SAF production may carry economic risks, akin to the initial rollout of any technology, there exists an investment opportunity and risk mitigation potential. This is where the interconnection of LCAF and SAF comes into play. Furthermore, refineries are currently the largest users of hydrogen, which creates potential opportunities to invest in renewable hydrogen, whether for the production of LCAF or in harnessing that renewable hydrogen to generate SAF. In essence, LCAF and SAF are distinct but interconnected elements within the aviation industry's broader sustainability framework.

Figure 11: Quantifying the possible technology improvement of LCAF on carbon emissions



	Conventional Jet-Fuel	LCAF
Jet fuel combustion	73.8	73.8
Crude oil production	8.6	4.5
Crude oil refining	4.5	2
Crude oil transportation	1	0.5
Jet fuel distribution	0.8	0.7

Source: Author's analysis of data from [40]

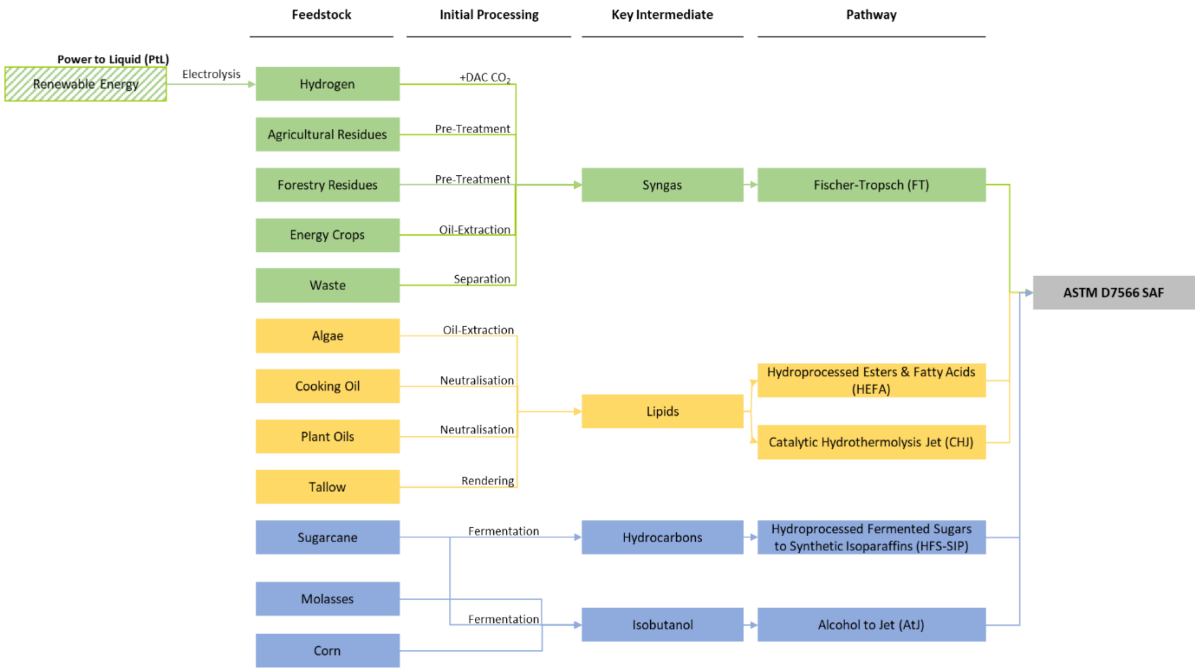
As can be seen in Figure 11, LCAF is a strategic approach to reduce as many operational emissions as possible, recognizing that a substantial proportion of aviation emissions are embodied in the ignition of the fuel itself. Nonetheless, LCAF presents an opportunity for refineries to co-produce and process SAF into existing fuel streams, facilitating a smoother transition toward greener aviation fuel sources. Moreover, it is worth noting that while LCAF with emissions at 80 gCO2e/MJ may not seem like a significant contribution to GHG emissions reductions, this reduction would be comparable in effect to efficiency gain that was only seen in the 1970s when the 747 was introduced with its HBR turbofan engines. In addition, approximately five billion litres of LCAF could potentially offer reductions equivalent to approximately one billion litres of SAF with emissions at 45 gCO2e/MJ. Indeed, this highlights an important aspect often overlooked when considering decarbonization, which is the transitional phase for an industry that is striving for continued growth. In this context, LCAF inherently possesses a complementary nature. It serves as an immediate transitional fuel, as it primarily focuses on building on the existing fuel-supply value chain while also facilitating the growth of SAF in existing refineries. This transition may require minimal changes in the broader commercial aviation landscape. LCAF could indeed serve as a vital component in the journey toward a more sustainable and environmentally responsible aviation industry.

2.2.2 Sustainable aviation fuels

Before delving into the discussion of hydrogen's role in SAF production, it is crucial to grasp that SAF, as per ICAO, refers to aviation fuel derived from renewable or waste sources and is subject to specific sustainability criteria detailed in Annex 16 Volume IV of CORSIA.[41] Presently, SAF is certified in accordance with the ASTM D7566 standard. In the aviation fuel industry, ASTM serves as the international standard for jet fuel quality, and plays a crucial role in ensuring safety, quality, and reliability of SAF. It is worth noting that the definition of SAF could evolve over time, depending on the consensus among ICAO member countries participating in CORSIA. Furthermore, the approved methods for SAF production may broaden as the aviation industry progresses.

Currently, there are eleven approved methods for producing SAFs that are recognized by CORSIA, falling under the ASTM D7566 Annex 1 to 8 and D1655 Annex A1,[42] most of which can be seen in Figure 12. These ASTM-approved pathways include Hydroprocessed Esters and Fatty Acids (HEFA), Gasification and Fischer-Tropsch (FT), Alcohol to Jet (AtJ), Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP), and Catalyzed Hydrothermolysis Jet (CHJ). The importance of these ASTM standards lies in their role as a reference point for the aviation industry and regulatory bodies. ASTM standards ensure the quality, consistency, and safety of SAFs, allowing for their widespread adoption in the aviation sector. Indeed, these standards help in making sure that SAFs meet specific criteria, such as composition, performance, and emissions reductions.

Figure 12: Methods for SAF production



Source: Adapted from [43]

Among these pathways, the most commonly used method for commercial SAF production is the HEFA pathway, although some FT-based SAFs are also available, albeit in smaller quantities. Each of these pathways, except for HFS-SIP, results in the production of a synthetic paraffinic kerosene (SPK), which can be readily blended with conventional jet fuels. Most of these pathways allow for blending of up to 50 per cent SAF (subject to current regulatory limits), while HFS-SIP and Hydrocarbon-Hydroprocessed Esters and Fatty Acids (HC-HEFA) are approved for up to 10 per cent blends. More details can be found in the ASTM D7566 standard. In the FT pathways (FT-SPK, FT-SKA), the feedstock is thermally converted into syngas, which is a mixture of hydrogen and carbon monoxide. The syngas then undergoes a series of iron/cobalt-

[41] ICAO. (2023a). https://www.icao.int/environmental-protection/pages/SAF.aspx
[42] ICAO. (2023c). https://www.icao.int/environmental-protection/GFAAF/Pages/Conversion-processes.aspx
[43] Roland Berger. (2020). 'Sustainable Aviation Fuels - the best solution to large sustainable aircraft?' https://www.rolandberger.com/publications/publication_pdf/roland_berger_sustainable_aviation_fuels.pdf

catalyzed reactions to synthesize kerosene. In HEFA pathways (HEFA, HC-HEFA), oils are treated with hydrogen to reduce and isomerize them into suitable hydrocarbons, which are subsequently cracked and fractionated to create an appropriate blend of paraffins for jet fuel. The CHJ pathway follows a similar process using lipid intermediates to HEFA. It reacts lipids with water under extreme temperatures and pressures to produce a mixture of hydrocarbons. ATJ and HFS-SIP both involve fermenting carbohydrate feedstocks with additional secondary reactions and purification steps, resulting in different intermediates and products. Notably, HFS-SIP does not directly produce synthetic paraffinic kerosenes.[43][44]

Interestingly, the common misconception that hydrogen's role in SAF production is limited to the FT-based pathway is inaccurate. In fact, in nearly all SAF production pathways, the introduction of external hydrogen sources is necessary to facilitate various chemical processes that yield SAF. It is essential to recognize that while the quantities of required hydrogen may vary across these pathways, its utilization is integral to SAF production across the board.

Once SAF is produced, blended with regular jet fuel, and certified under the ASTM D7566 standards, users become eligible for carbon offset credits through CORSIA. Notably, SAF can be handled just like traditional aviation fuel and can be easily mixed in the existing infrastructure. It is worth noting that the rationale behind the current blending limits is to ensure compatibility with the majority of airworthy commercial aircraft. The standard establishes limitations on specific compounds (e.g. aromatics, cycloparaffins, or trace compounds) that a fuel must adhere to in order to gain certification as aviation fuel, meeting its secondary functions of lubrication and sealing.[45] Nonetheless, this is anticipated to become less of a concern as older aircraft fleets retire, and the engines of new fleet aircraft do not impose the same constraints.[46]

Compared to its alternatives, it becomes evident that SAF is not only a promising alternative to conventional aviation fuels but a vital component in the aviation industry's ambitious journey toward sustainability. Entities like ICAO and the International Air Transport Association (IATA) foresee SAF playing a substantial role in this transformation.[3][4]

3. State of SAF in the aviation landscape

SAF stands out as one of the few viable options within the aviation industry that is gaining significant momentum, especially when we analyze recent policy developments. By October 2023, major global players, including the United States, European Union, United Kingdom, China, India, UAE, Brazil, Canada, and Indonesia, have either announced SAF mandates or are actively in the process of developing them (see Annex A1 for more detailed information). This surge in SAF-related policies is indicative of a growing trend, even though there may be variations in the specifics of these mandates. What truly impresses is the concentrated effort made within the past five years, with the number of such policies increasing year on year.[47] Furthermore, when examining the availability of SAF at airports, as of 2023, there are 69 airports worldwide that have ongoing SAF deliveries, with an additional 40 airports in the process of receiving SAF in batches. This is a remarkable shift from the situation in 2015 when only one airport had received any SAF deliveries.[48]

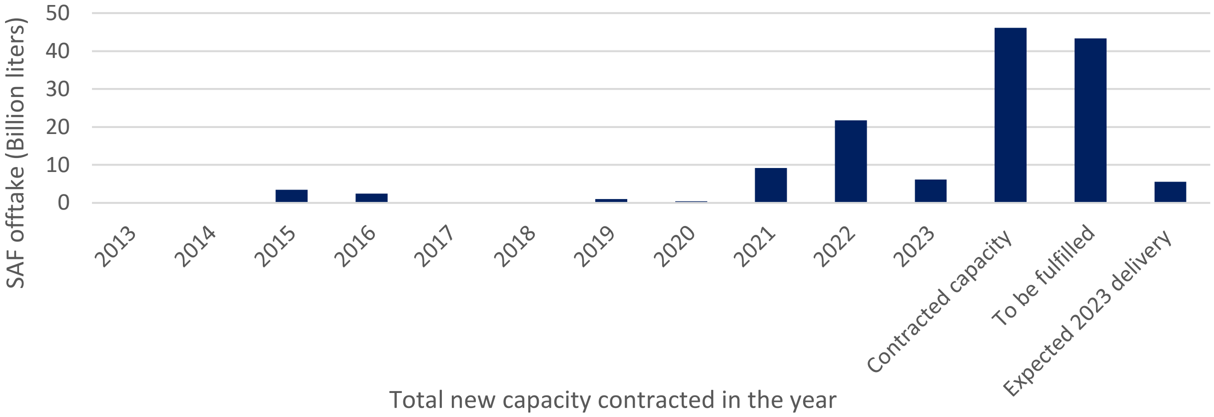
Transitioning from the realm of policy to examining contractual agreements, the landscape offers a more granular view of the commitments and targets. As of 2023, the volume of SAF specified in active off-take agreements exceeds 46 billion litres, with contract durations spanning from single deliveries to extended

---

[44] IATA. (n.d.). 'Sustainable Aviation Fuel: Technical Certification.' https://www.iata.org/contentassets/d13875e9ed784f75bac90f000760e998/saf-technical-certifications.pdf
[45] ACI-ATI. (2022). 'ACI-ATI Integration of Sustainable Aviation Fuels into the Air Transport System.' https://store.aci.aero/product/aci-ati-integration-of-sustainable-aviation-fuels-into-the-air-transport-system/?_gl=1%2Ax87lb4%2A_ga%2ANTUwNjgwMzc2LjE2OTcxNTAyNTI.%2A_ga_XTCVT8VT6K%2AMTY5NzM2OTY3My40LjAuMTY5NzM2OTY3My42MC4wLjA.
[46] Hailey, R. (2022). 'First A380 powered by 100% SAF takes to the skies.' https://rogistics.net/first-a380-powered-by-100-saf-takes-to-the-skies/
[47] ICAO. (2023d). 'Environmental Policies on Aviation Fuels.' https://www.icao.int/environmental-protection/GFAAF/Pages/Policies.aspx
[48] ICAO. (2023e). https://www.icao.int/environmental-protection/GFAAF/Pages/Airports.aspx

20-year arrangements.[49] Among these diverse contractual commitments, based on an assumption of average yearly delivery amounts, we can anticipate the potential delivery of approximately 5.5 billion litres of SAF within the 2023 calendar year. This assumption, while not necessarily conservative, provides a projection for which SAF could account for roughly 1.5 per cent of the total jet fuel delivered.[50] The historical trends of contracted SAF amounts are depicted in Figure 13, providing context into the evolution of these agreements over time.

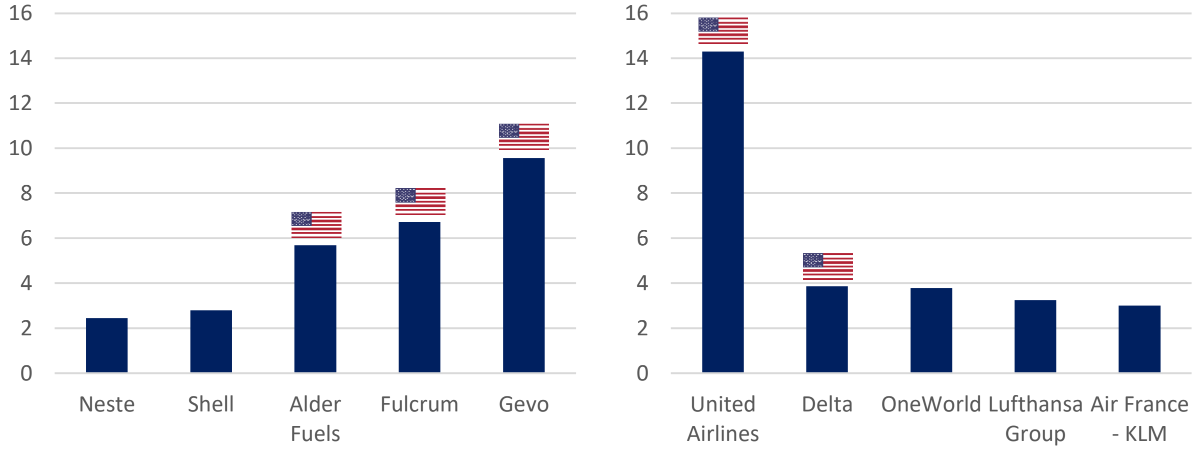
Figure 13: Historical contracted SAF off-take agreements (billion litres)



Source: Author's analysis of [49]

As evident from the Figure 13, there is a discernible uptick in contracted SAF since 2020, mirroring a trend seen in the publication of policies during the same period. Furthermore, when we investigate potential geographical correlations between SAF production and usage, it becomes apparent that the United States, source for the largest aviation emissions, is currently host to the largest and most long-standing SAF contracts.[49] This correlation is represented in Figure 14, providing an illustration of this aspect of the SAF landscape.

Figure 14: Largest five producers and off-takers by SAF contracted (billion litres)



Source: Author's analysis of [49]

When examining the supply side, it is evident that the predominant contract suppliers, with the exception of Shell, are specialized SAF producers. On the off-take side, the major stakeholders are prominent international airlines, holding the lion's share of the contracts.

Shifting our focus from contracts to projected SAF capacity, there are various estimates regarding the potential market share SAF could attain in the next decade and by 2050. When considering ICAO, in its

---

49 ICAO. (2023f). 'SAF Offtake Agreements.' https://www.icao.int/environmental-protection/GFAAF/Pages/Offtake-Agreements.aspx
50 Lagerquist, J. (2023). 'Jet fuel to dominate oil demand growth in 2023: Capital Economics.' https://ca.finance.yahoo.com/news/jet-fuel-dominate-oil-demand-growth-2023-capital-economics-161347301.html

LTAGs report scenarios, it is stated that SAF could represent a significant portion, ranging from 27 per cent to 98 per cent, of total international aviation energy use by 2050.[4] IATA, on the other hand, states that SAF would contribute significantly in its ambitions toward achieving net-zero emissions, where 65 per cent of emissions reductions are expected to be achieved through the deployment of SAF.[3]

While SAF is projected to account for a significant share of the aviation fuel supply by 2050, questions arise regarding the potential availability of the resources used in SAF production. Initially, when examining feedstock availability for SAF, it seems that there are no substantial technical barriers associated with resource availability. For instance, by 2030, biomass sourced from crops and waste could potentially meet 120 per cent of the global jet fuel demand.[51] However, upon closer examination, complexities surface that require attention. Firstly, the HEFA process currently constitutes 85 per cent of SAF production.[52] Nevertheless, studies indicate that this process is nearing its resource scalability limits.[5] Secondly, when considering biomass crops, primarily energy crops used for SAF production, challenges arise due to competition with other chemicals like biodiesel and naphtha.[53] Furthermore, the scalability of energy crops often comes at the expense of reducing acreage available for food crops, intensifying competition between the two and diminishing the potential availability of energy-crop-based SAF. Nonetheless, as depicted in Figure 12, the direct utilization of hydrogen and CO_2 for SAF production holds promise in enhancing feedstock availability in the long term.

However, it is crucial to underscore the substantial challenges that lie ahead. Hydrogen, which plays a vital role in nearly all SAF production pathways, is pivotal in enabling the aviation industry to achieve Net-Zero emissions by 2050, as delineated in IATA's analysis of the LTAG report scenarios. This ambitious goal may necessitate over 100 million tonnes per year (Mt/y) of hydrogen by 2050,[54] roughly equivalent to the entire current global hydrogen production, where a significant portion of this hydrogen would be allocated to the various SAF production pathways.

When exclusively considering SAF using a renewable hydrogen as the main feedstock, such as Power-to-Liquid (PtL) SAF, projections indicate that by 2030, annual production, as suggested by SkyNRG, a SAF distributor, could reach up to 8 per cent.[5] Looking further into the future, a report from the Air Transport Action Group (ATAG) forecasts that PtL SAF could account for 42-57 per cent of SAF production by 2050.[55] However, this assessment only takes into account hydrogen used as the primary feedstock, combined with waste or atmospheric CO_2 to make SAF. Still, as mentioned earlier, hydrogen plays a crucial role in the processing and refining of most SAF pathways, and the growth of the SAF value chain will be closely linked to the development of decarbonized and renewable hydrogen.

We have not extensively discussed the issue of SAF costs, as this area warrants in-depth investigation in future research. However, in a brief review, it is noteworthy that SAF currently costs approximately twice as much as conventional jet fuel. Without some form of subsidy or support, investing in SAF may not make economic sense. The United States is taking a prominent role in SAF deals due to its provision of direct subsidies to producers. However, if initiatives such as CORSIA were to take effect, mandating the use of CO_2 credits for airlines, and taking into account the fact that airline profit margins usually remain in the single-digit percentage range, this could compel airlines to pass on the additional costs to passengers. Such a move might result in airlines, especially those known for serving price-sensitive customers, facing the risk of slipping into negative profit margins and ultimately being forced out of their market segment. This scenario could potentially lead to the emergence of industry 'super-majors' to rescue the sector, if governments aim to avoid bailouts or opt out of foreign investment buy-outs. This structural shift may impact the adoption of decarbonization practices, mirroring past turmoil in the automotive sector during the early 21st century when major car producers required bailouts. While speculative, it underscores the importance of early support

[51] EY. (2023). 'Sustainable aviation fuel (SAF) on the rise.' https://assets.ey.com/content/dam/ey-sites/ey-com/en_us/topics/aerospace-and-defense/ey_saf_whitepaper_final.pdf?download
[52] IATA. (2023c). https://www.iata.org/en/pressroom/2023-releases/2023-12-06-02/
[53] Dimitriadou, E. and Lavinsky, C. (2022). 'Long-term demand for SAF could run into supply constraints.' https://www.spglobal.com/commodityinsights/en/market-insights/blogs/oil/032222-sustainable-aviation-fuel-saf-2050
[54] IATA. (2023d). 'Energy and New Fuels Infrastructure – Net Zero Roadmap.' https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/energy-and-new-fuels-infrastructure-net-zero-roadmap.pdf
[55] ATAG. (2021). 'Waypoint 2050, Air Transport Action Group.' https://aviationbenefits.org/environmental-efficiency/climate-action/waypoint-2050/

from governments to achieve sustainable fuel decarbonization in aviation while maintaining a competitive market that avoids both over-competitiveness and the emergence of dominant industry players.

Conclusion

The aviation industry stands at a pivotal juncture in its quest for sustainability and reduced carbon emissions. As we navigate the challenges of climate change and environmental responsibility, several alternative propulsion methods emerge as potential solutions to decarbonizing this vital sector.

The advent of battery-electric power systems and their potential adoption in aviation offers a glimpse into a greener future. However, their feasibility in addressing the vast energy demands and infrastructure requirements of the aviation industry remains a subject of ongoing research and development. The environmental and social sustainability impacts of battery production, including critical mineral mining, underscore the significant challenges associated with sustainable battery-powered flight.

Hydrogen-powered flight, whether through combustion or fuel cell technologies, has gained significant momentum in recent years. Ambitious projects like Airbus' ZEROe initiative and advancements in hydrogen engine technology are promising steps toward reducing emissions and pushing the boundaries of aviation innovation. However, the rollout of hydrogen-powered aircraft and the development of necessary infrastructure will take time, leading to constraints within the timeframe for achieving complete decarbonization by 2050 solely through this propulsion method.

CORSIA, the international initiative to offset and reduce carbon emissions in aviation, introduces measures to monitor and mitigate the industry's carbon footprint. SAFs and LCAFs play a vital role in reducing GHG emissions in aviation without causing major shifts in how aircraft operate today. Furthermore, the aviation industry is gaining momentum in advancing the SAF value chain, with an increasing number of countries implementing SAF mandates and expanding their usage at airports. The growing dedication to SAF production and utilization signifies a notable shift towards sustainability within the sector. Long-term projections indicate that SAFs, including hydrogen-based varieties, will play a crucial role in attaining net-zero emissions and mitigating the environmental impact of aviation.

In summary, the aviation industry is making significant strides in adopting alternative propulsion technologies and sustainable fuels to mitigate its environmental impact. However, there is still a considerable journey ahead.

Appendices

Annex A1 – Current SAF Polices

Table 1: SAF polices as of October 2023

Date	State	Policy Title	Policy Description	Status	Source
25-Sep-23	United States	FAST-SAF and FAST-TECH Grant Programme	The Department of Transportation (DOT), Federal Aviation Administration (FAA) announces the opportunity to apply for funds for the FAA Fueling Aviation's Sustainable Transition (FAST) Grant Program, established under Section 40007 of the Inflation Reduction Act of 2022. The grant program will have elements focused on sustainable aviation fuel (SAF), to be termed FAST-SAF, and elements focused on low-emission aviation technologies, to be termed FAST-Tech. The amount of available funding for the FAST Grant Program is $244.53M and $46.53M for FAST-SAF and FAST-Tech, respectively. The purpose of the FAST Grant Program is to make grants available to eligible entities for projects that support sustainable aviation fuels and low-emission aviation technologies in line with the goals of the United States Aviation Climate	Adopted	Link
15-Sep-23	Brazil	ProBioQAV	Brazil's President Luiz Inácio Lula da Silva, mines and energy minister Alexandre Silveira and other ministers have signed a fuel program bill, which will be sent to Congress. The bill establishes the national sustainable aviation fuel program (ProBioQAV) to encourage the production and use of SAF, obliging airline operators to reduce carbon dioxide emissions by 1% from 2027, reaching a 10% reduction by 2037. This reduction should be achieved by increasing the mixture of SAF with fossil aviation kerosene.	Under development	Link
13-Sep-23	Regional (European Union)	RefuelEU	Fuel suppliers must ensure that 2% of fuel made available at EU airports is SAF in 2025, rising to 6% in 2030, 20% in 2035 and gradually to 70% in 2050. From 2030, 1.2% of fuels must also be synthetic fuels, rising to 35% in 2050. Synthetic fuels are made using captured CO2 emissions, which proponents say balances out the CO2 released when the fuel is combusted in an engine.	Adopted	Link Link Link Link Link
4-Sep-23	United Kingdom	Revenue certainty scheme	The government has committed to introduce a revenue certainty scheme as part of the UK's world-leading sustainable aviation fuel (SAF) programme, helping create new jobs and grow the economy as part of the Energy Bill, the government has tabled legislation that will launch a consultation on options for designing and implementing the scheme this will positively contribute towards government's ambitious commitment of having at least 5 commercial SAF plants under construction in the UK by 2025 and cement the UK's status as a world leader in this industr	Under development	Link
19-Apr-23	India		Mandate being considered for 1% blending of sustainable aviation fuel by 2025, 2% by 2026, and 5% by 2030	Under development	Link
15-Feb-23	Japan		Japan's campaign to cut greenhouse gas emissions is extending to the skies, as the government aims to have	Adopted	Link

			airlines replace 10% of their jet fuel with eco-friendlier alternatives by 2030.		
13-Feb-23	United States (Illinois)	Invest in Illinois Act	This legislation in Illinois provides a tax credit of $1.50 per gallon for SAF used by aircraft in the state. For the SAF to qualify for the credit, it must reduce carbon emissions by at least 50% throughout its life. The credit applies to all SAF used in Illinois, regardless of where it is produced. However, credits for SAF used before June 1, 2028, must come from renewable sources such as biomass, waste streams, renewable energy, or gaseous carbon oxides. The tax credit will be available until January 1, 2033.	Adopted	Link
10-Feb-23	United States (Washington)		The bill aims to create a preferential business and operations (B&O) tax rate of 0.275 percent for the manufacturing and wholesaling of alterative jet fuels. The B&O tax is Washington's major business tax. According to a legislative documents, the B&O tax is imposed on the gross receipts of business activities conducted within the state, without any deduction for the cost of doing business. Some current B&O tax rates include 0.471 percent for retailing and 0.484 percent for manufacturing, wholesaling and extracting. The bill would also establish a B&O and public utilities tax credit for certain sales and purchases of alternative jet fuel. The amount of the credit would be $1 per gallon of alterative jet fuel that has at least 50 percent less carbon dioxide equivalent emissions than conventional jet fuel. The credit would increase by 2 cents for each additional 1 percent reduction beyond 50 percent, with a cap of $2 per gallon. Eligibility for the credit for sales of alternative jet fuel would be limited to businesses located in a qualifying county or a businesses' designated alternative jet fuel blender located in Washington. A qualifying county is a county that has a population of less than 650,000. The credits could only be earned on purchases of alternative jet fuel for flights departing Washington.	Adopted	Link
20-Jan-23	United Arab Emirates	National Sustainable Aviation Fuel Roadmap of the United Arab Emirates, 2022-2050	The UAE published their National SAF Roadmap for 2022 to 2050, including an ambition of developing a domestic SAF production capacity sufficient to supply 700 million liters SAF on an annual basis by 2030.	Adopted	Link
16-Nov-22	India		SAF mandate blending under consideration for domestic aviation	Under development	Link
18-Oct-22	Japan		The Japanese government is seeking public comments on a draft policy to promote decarbonization in the aviation industry. The policy, in part, would require flights to be carbon neutral by 2050 and require airlines to use sustainable aviation fuel (SAF).	Under development	Link
3-Oct-22	China	China Civil Aviation Green Development	Target of 50k tons of SAF use by 2025 SAF performance testing, airworthiness certification, exploration of new paths for its development.	Adopted	Link

		Policy and Action			
16-Aug-22	United States	Inflation Reduction Act (SAF blenders tax credit)	The bill provides a $1.25 per-gallon credit for each gallon of SAF sold as part of a qualified fuel mixture, including that it has a demonstrated lifecycle greenhouse gas (GHG) reduction of at least 50 percent compared to conventional jet fuel. The credit, available for two years beginning January 1, increases up to $1.75 per gallon on a sliding scale based on the percentage of lifecycle GHG emissions reduced beyond 50 percent. Beginning in 2025, SAF would be eligible for credits up to $1.75 per gallon under a new Clean Fuel Production Credit (CFPC). That credit is set to expire at the end of 2027.	Adopted	Link
19-Jul-22	United Kingdom	Jet Zero Strategy	Increasing support for sustainable aviation fuels (SAF), by creating secure and growing UK SAF demand through a SAF mandate that will require at least 10% of jet fuel to be made from sustainable sources by 2030 and kickstarting a domestic SAF industry, supported by the new £165 million Advanced Fuels Fund.	Adopted	Link
18-May-22	Brazil	Brazil	Brazilian sustainable aviation fuel mandate that will take effect in January 2027 will target cutting Brazil's airline emissions by 1% of the sector's 2026's total emissions, with the possibility of raising that figure to 10%	Under development	Link
7-Apr-22	United States	Renewable Diesel and Sustainable Aviation Fuel Parity Act	The Renewable Diesel and Sustainable Aviation Fuel Parity Act of 2022 will: Require the Energy Information Administration to report on U.S. production and foreign imports of renewable diesel and sustainable aviation fuel, including the type, origin, and volume of feedstocks used for these fuels; Allow renewable diesel and sustainable aviation fuel production facilities to qualify for the Department of Energy’s Title XVII loan guarantees under the Energy Policy Act of 2005; and Exempt renewable diesel that meets the same technical specifications as petroleum-based diesel from the labeling section of the Energy Independence and Security Act of 2007.	Overridden by IRA	Link
2-Jan-22	Denmark		Denmark Targets 2030 For Fossil Fuel-Free Domestic Flights	Under development	Link
25-Nov-21	Brazil	National Biokerosene Programme	The policy directs federal agencies and institutions to provide resources to SAF projects, as well as fiscal incentives.	Adopted	Link
16-Jul-21	Regional (European Union)	ReFuelEU	Proposed mandate of SAF use, starting from 2% in 2025 up to 63% in 2050	Under development	Link Link
13-Jun-21	New Zealand	Sustainable Biofuels Mandate	Proposed policy requires fuel suppliers to reduce the GHG emissions from transport fuels by a defined percentage each year. It applies to all transport fuels, including domestic aviation fuel, and requires biofuels to meet sustainability criteria to certify that they do not impact on food production or indigenous biodiversity. It requires fuel suppliers to prepare annual reports to demonstrate compliance. There will be penalties for non-compliance, although there is some flexibility for fuel suppliers, including	Under development	Link

			the ability to trade emissions reductions with each other, and to defer for two years.		
20-May-21	United States	Sustainable Skies Act	Tax incentive of up to $2.00 for every gallon produced of sustainable aviation fuel. The bill introduced by Whitehouse aims to create a grant program authorized at $1 billion over five years to expand the number of facilities producing SAF and build out the necessary supporting infrastructure.	Under development	Link Link Link
18-Dec-20	Canada	Clean Fuel Standard	The Clean Fuel Standard will require liquid fossil fuel primary suppliers (i.e., producers and importers) to reduce the carbon intensity of their liquid fossil fuels used in Canada from 2016 carbon intensity levels. In 2022 the carbon intensity reduction requirement will start at 2.4 gCO2e/MJ. It will gradually increase over time reaching 12 gCO2e/MJ in 2030. To achieve this, fuel producers will need to provide innovative solutions and new fuel options to consumers.	Under development	Link
12-Dec-20	France	France	SAF roadmap to reach a SAF supply of 1% by 2022, 2% in 2025 and 5% in 2030. Focus on advanced feedstocks	Under development	Link Link
25-Sep-20	Germany	Germany	National legislation for GHG-reduction of fuels (to transpose the RED II) and the German National Hydrogen Strategy foresee a SAF energetic sub-quota of 2 % in 2030 and ONLY for PtL-kerosene.	Under development	Link Link
11-Sep-20	Sweden	Sweden	A carbon neutral country by 2045. Legislative proposal for 0.8% GHG reduction mandate in 2021, and gradually increase to 27% by 2030.	Under development	Link Link
8-Sep-20	Portugal	Portugal	Roadmap for Carbon Neutrality (RNC2050): integrated approach to transport decarbonisation including aviation	Under development	Link Link
8-Sep-20	Spain	Spain	Climate Change Law: 2% SAF supply objective in 2025. Several new bio-refineries under planning with special focus on wastes and residues.	Under development	Link Link
8-Sep-20	Netherlands	SAF roadmap	SAF Roadmap under development with a blending mandate at the national -or EU- level. Focus on advanced feedstocks.	Under development	Link Link
13-Jul-20	Canada (British Columbia)	Renewable & Low Carbon Fuel Requirements Regulation	The BC-LCFS sets CI targets that decline each year.The Act does not currently recognize GHG reductions within the aviation and marine fuel sectors, so the Ministry is considering whether to expand the BC-LCFS to include these reductions and provide support for low carbon fuel development by adding two additional fuel classes: jet fuel class and marine fuel class.	Under development	Link Link
19-Nov-19	Norway	Norway	SAF blend 0,5% mandate started in 2020. Considering a 30% target for 2030.	Adopted	Link Link
4-Jun-19	Finland	Finland	A carbon neutral country by 2035: Increasing SAF obligation to reach 30% in 2030.	Under development	Link Link

27-Sep-18	United States (California)	Low Carbon Fuel Standard (LCFS)	crediting for fuel pathways and projects, based on a carbon intensity score	Adopted	Link Link
27-Jun-18	ICAO (International)	CORSIA	CORSIA allows airines to reduce their offsetting requirements with the use of CORSIA eligible fuels, which include Sustainable Aviation Fuels and Lower Carbon Aviation Fuels.	Adopted	Link
18-Apr-18	United Kingdom	Renewable Transport Fuel Obligation (RTFO)	The Renewable Transport Fuel Obligation (RTFO) rewards SAF production with the same economic incentives given to road vehicles.	Adopted	Link Link
1-Jan-13	Indonesia	Indonesia	Mandate of 5% SAF use by 2025	Adopted	Link