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## **Air Transport and Environmental Sustainability: What are the Challenges to Meet Net Zero Emissions by 2050?**

**Bijan Vasigh**

Joseph R. Martin, Distinguished Professor of Aviation Management, Department of Accounting, Economics, Finance, and Information Sciences, Daytona Beach Florida, United States  
E-mail: [vasighb@erau.edu](mailto:vasighb@erau.edu)

**Evangelia Pantelaki**

Assistant Professor in Economics, Department of Economics and Finance, United Arab Emirates University, Al Ain, United Arab Emirates  
E-mail: [evangelia@uaeu.ac.ae](mailto:evangelia@uaeu.ac.ae)

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### **Abstract**

The aviation industry has experienced sustained growth over the past five decades, resulting in a significant increase in CO<sub>2</sub> emissions. From relatively modest levels in the 1970s, aviation emissions have risen more than fivefold, reaching approximately 1.0–1.1 gigatonnes of CO<sub>2</sub> in 2019. Although COVID-19 pandemic caused a temporary decline in emissions, recovery in air travel demand has pushed emissions close to pre-pandemic levels. This study explores sustainable aviation fuels alongside complementary measures, including technological advancements in aircraft design, and future propulsion systems such as hydrogen and electric aircraft. Despite its potential for near term deployment, SAF faces challenges related to cost of production, scalability, and infrastructure. This paper concludes that achieving net-zero emissions by 2050 will require a coordinated, multi-layered approach combining policy support, technological innovation, and large-scale investments.

Keywords: sustainability, aviation, fuel consumption, aircraft design, net zero  
Jel Codes: R41, Q01, Q42, Q52

### **1. Introduction**

Over the past several decades, global aviation (carbon dioxide) CO<sub>2</sub> emissions have grown significantly, showing the steady expansion of air travel and international connectivity (Figure 1). In the 1970s, emissions were relatively limited, below 200 million tonnes annually, reflecting the early stages of commercial aviation's global development. By 1990, this figure had climbed to roughly 400–500 million tonnes per year, fueled by increasing globalization and the liberalization of air transport markets. The upward trajectory continued into the 2000s, with emissions reaching approximately 600–700 million tonnes annually and rising further to around 800–900 million tonnes by 2010, driven largely by strong growth in passenger demand, particularly in emerging economies. From the modest beginnings in the 1970s, aviation emissions have expanded more than fivefold,



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peaking at about 1.0–1.1 gigatonnes of CO<sub>2</sub> in 2019. While the COVID-19 pandemic led to a temporary decline, the rebound in air travel has brought emissions back close to pre-pandemic levels.

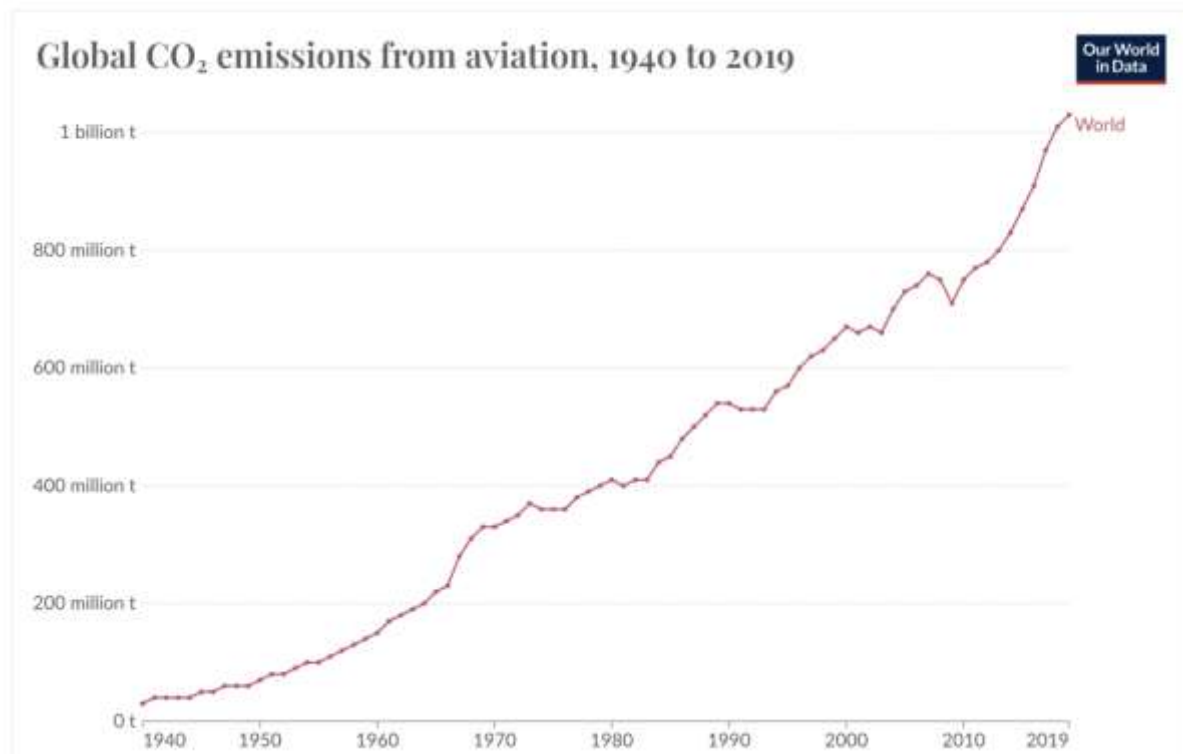


Figure 1. Global emissions from aviation 1940-2019

Source: Our world in data (2024)

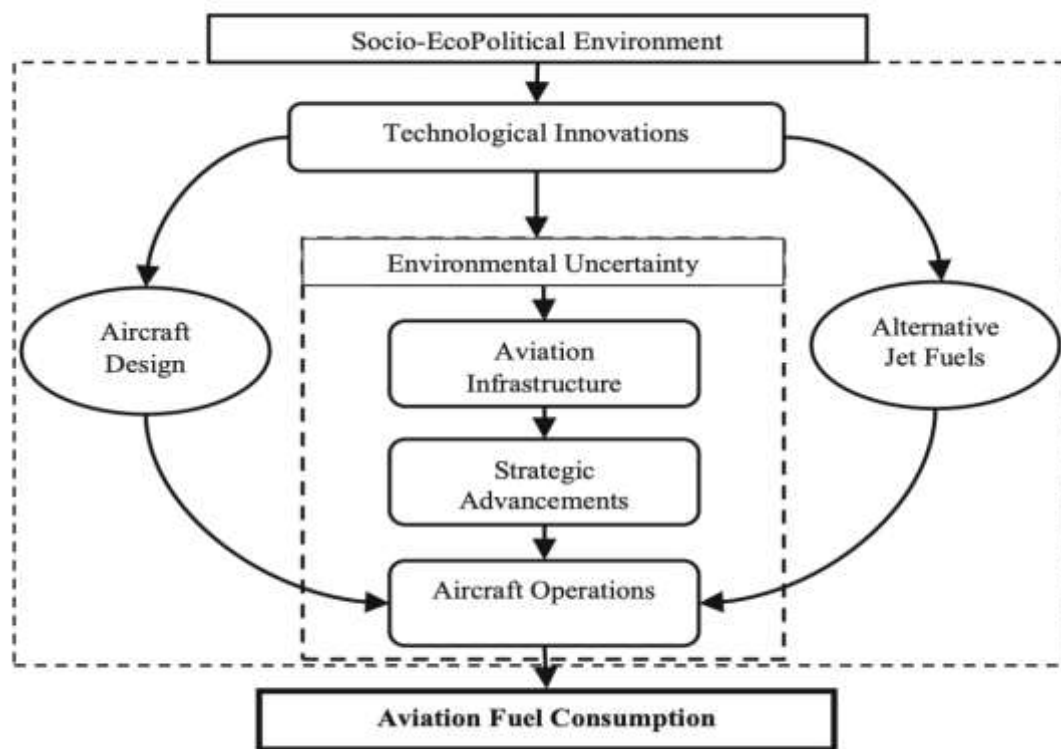
Recent projections from International Air Transport Association (IATA) show that the global air travel demand is expected to more than double by 2050 (IATA, 2026-a). More specifically, between 2024-2050 the compound annual growth rate (CAGR) is expected to range between 2.9 and 3.3 percent confirmed by three different modelling scenarios exploring factors such as long-term economic growth, populations, aviation fuel price trends, the global energy transition, and air transport supply-side capacity development. Obviously, regional differences in air travel growth are present. More specifically Asia-Pacific and Africa are expected to be the fastest-growing regions over 2024-2050, with CAGRs of 3.8 and 3.6 percent while Europe and North America are projected to grow more slowly with CAGRs of 2.5 and 2.8 percent.

Aviation industry leaders face huge challenges on how to satisfy the increasing air travel demand while at the same time ensure that they can reach the environmental sustainability targets of the industry. This paper presents and critically analyses the available strategies for reducing greenhouse gas emissions in the aviation sector, with the objective of achieving net-zero emissions by 2050. It places particular emphasis on sustainable aviation fuels (SAF) as a key near- to medium-term solution, given its potential to reduce lifecycle emissions by up to 80 percent while remaining compatible with existing aircraft fleets (IATA, n.d.). Additionally, this study considers complementary approaches, including advances in aircraft technology and emerging propulsion systems such as hydrogen and electric aircraft. The paper concludes that reaching net-zero emissions by 2050 will require a coordinated, multi-layered approach that combines operational efficiency, technological innovation, and strong long-term policy support.

## 1. Aviation fuel consumption

Jet fuel remains one of the largest operating expenses in commercial aviation, accounting for approximately 25–30 percent of total airline operating costs in many regions (IATA, 2026-b). Graph 1 shows the complex ecosystem which affects aviation fuel consumption (Singh et al., 2019). Aircraft design and alternative jet fuels are the main technological innovations that lead improvements in fuel consumption and those that we are focusing on this study. Both are feeding the aircraft operations which are influenced by environmental uncertainty such as aviation infrastructure and strategic advancements.

Operational efficiency is considered one of the key pillars of aviation's environmental strategy, through with fuel conservation is targeted (EASA, n.d.-b). Fuel conservation is defined as the process of managing the operation and condition of an airplane to minimize the fuel used on every flight (Boeing, 2006). ICAO (n.d.-a) recommends a basket of measures to achieve its Long-Term Aspirational Goal (LTAG) of net-zero CO<sub>2</sub> emissions by 2050. As regards, the reductions in fuel burn and CO<sub>2</sub> emissions, the basket refers to a list of measures for aircraft's on-board weight management and operational strategies. Notably, aircraft weight reduction is an important concept and even small reductions in weight can have a meaningful impact; for instance, saving one kilogram of weight can translate into \$4,210 in fuel savings per year for every kilogram saved<sup>1</sup>(ATLEurope, n.d.). The operational measures are classified in reducing emissions at gate, taxi-out phase, climb phase, cruise phase, descent phase and finally in the taxi-in phase (ICAO, n.d.-a). Each phase of the flight entails a wide range of measures<sup>2</sup>.



Graph 1. Factors driving aviation fuel consumption

Source: Singh et al. (2019)

As an example, researchers used data from the domestic air transport system in Brazil and found that operational efficiency with optimal fleet assignment can further reduce fuel consumption by approximately 1.3-2.9 percent (Eskenazi et al., 2024). Similarly, Wandelt et al. (2025) evaluated the fuel consumption implications of various

<sup>1</sup> The model is based on the following assumptions: Flight distance approximately 1,140 km per flight, flight frequency about 5 flights a day, or roughly 1,825 flights annually, for or each 1 kg of weight reduction, fuel burn is reduced by approximately 0.003 kg per kilometre, fuel cost averaging around \$0.675 per kg. Under these conditions, saving 1 kg of weight can lead to an annual fuel saving of roughly 6,241.5 kg (ATLEurope, n.d.).

<sup>2</sup> For specific practices in each phase see ICAO (n.d.-a) and Boeing (2006).

global passenger reassignment and replacement scenarios. The authors found that with the current technology, the fuel usage in global air transport could be reduced by more than one third. Furthermore, limiting passenger reassignment and aircraft replacements within the scope of a single airline, the maximum achievable reduction in global fuel consumption is estimated to be 19 percent. The next section presents the developments in aircraft design for a clear understanding of how the fuel consumption has improved in the decades since 1970's.

## 2. Aircraft design

Over the past five decades, commercial aviation has experienced substantial improvements in fuel efficiency, driven by advances in propulsion systems, aerodynamics, and aircraft design. Fuel burn per seat-mile has decreased dramatically, from approximately 0.30 kg in early jets to as low as 0.06–0.10 kg in modern aircraft, reflecting an overall efficiency improvement of nearly 80 percent over six decades as shown in Table 1.

The first generation of commercial jets, represented by aircraft such as the Boeing 707 and Douglas DC-8, established the foundation of modern air transport but were relatively fuel inefficient when compared with today's standards. These aircraft consumed approximately 0.30-0.35 kg of fuel per seat-mile. They were powered by low bypass ratio turbojet engines, which required large amounts of fuel and produced high levels of emissions. In the 1960s, the introduction of early-generation jet aircraft, including the Boeing 727 and early variants of the Boeing 737, marked an important step forward in commercial aviation efficiency. These aircraft achieved fuel consumption levels of approximately 0.20-0.25 kg of fuel per seat-mile, corresponding to an estimated 25–35 percent improvement over earlier first-generation jet designs. These gains were primarily driven by the adoption of early high-bypass turbofan engine concepts and incremental aerodynamic refinements, which together reduced drag and improved propulsive efficiency compared with earlier turbojet-powered aircraft (Lee et. al., 2021).

The 1980s and 1990s marked a period of substantial improvement in aircraft fuel efficiency with the introduction of second-generation jet aircraft such as the Boeing 737 Classic and the Airbus A320ceo. These aircraft reduced fuel consumption to approximately 0.12-0.16 kg of fuel per seat-mile, representing an improvement of roughly 40–50 percent compared to aircraft from the 1970s. This progress was driven primarily by the adoption of high-bypass turbofan engines, which significantly enhanced propulsive efficiency, along with advances in wing aerodynamics and structural design that reduced drag and weight (Lee et. al, 2021; ICAO, 2022).

During the early 2000s, further efficiency improvements were achieved with aircraft such as the Boeing 737 Next Generation, Airbus A330, and Boeing 777-200ER. These aircraft typically achieved fuel burn levels in the range of approximately 0.09-0.12 kg of fuel per seat-mile, reflecting continued but more incremental efficiency gains compared with earlier generations (IEA, 2020; ICAO, 2022). Overall improvements during this period were estimated at roughly 10–15 percent over preceding aircraft types, driven largely by refinements in turbofan engine efficiency, aerodynamic optimization, and operational improvements rather than disruptive technological change (Lee et. al, 2001; IPCC, 1999).

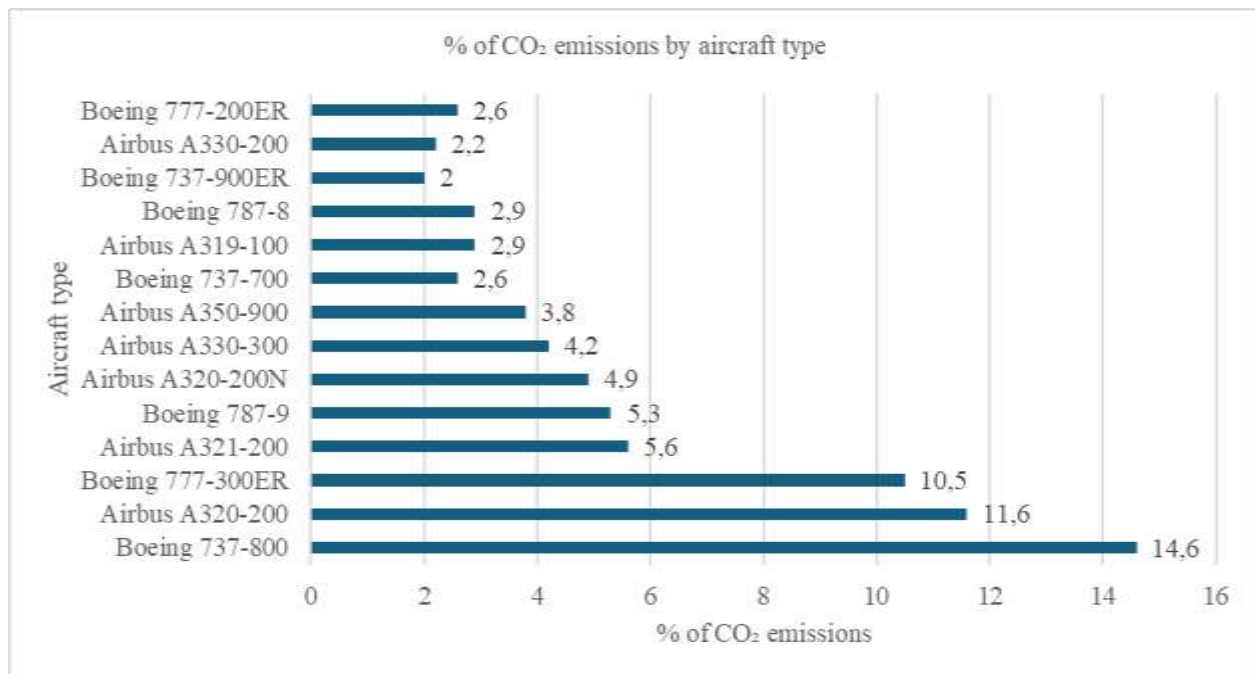
In the modern era, spanning from the 2010s to the 2020s, aircraft such as the Airbus A320neo and Boeing 737 MAX, Boeing 787, and Airbus A350 represent the most significant changes in efficiency since the 1980s. These aircraft typically consume around 0.07-0.10 kg of fuel per seat-mile, representing a 15–25 percent improvement over the previous generation. The Airbus A320neo achieves efficiency improvements through the use of next-generation engines, namely the Pratt & Whitney PW1100G and the CFM LEAP-1A, both of which incorporate higher bypass ratios and improved thermodynamic efficiency compared with earlier engine designs (about 15–20 percent better fuel efficiency). These gains are further enhanced by aerodynamic modifications such as Sharklet wingtip devices, which reduce induced drag and improve overall lift-to-drag performance (reducing drag by 3–5 percent). Similarly, the Boeing 737 MAX 8 employs CFM LEAP-1B engines alongside advanced aerodynamic features, including split scimitar winglets, which further reduce drag and improve fuel efficiency.

Table 1. Aircraft models and fuel consumption

| Generation                                | Example Aircraft                 | Fuel Burn per kg per seat-mile | Relative Efficiency Improvement              |
|-------------------------------------------|----------------------------------|--------------------------------|----------------------------------------------|
| Early Jet Age (1950s–1960s)               | Boeing 707, DC-8                 | 0.30–0.35 kg                   | Baseline (very inefficient turbojet engines) |
| First Generation Wide/Narrow Body (1970s) | Boeing 727, early 737, DC-9      | 0.20–0.25 kg                   | 25–35% better than Boeing 707                |
| Second Generation Jets (1980s–1990s)      | Boeing 737-300/400/500, A320ceo  | 0.12–0.16 kg                   | 40–50% improvement vs 1970s                  |
| Early 2000s Generation (2000s)            | Boeing 737NG, A330ceo, 777-200ER | 0.09–0.12 kg                   | 10–15% improvement vs 1990s                  |
| Modern Generation (2010s–2020s)           | A320neo, 737 MAX, 787, A350      | 0.07–0.10 kg                   | 15–25% improvement vs NG/ceo                 |
| Latest State-of-the-Art (2020s)           | A321neo LR/XLR, 787-9/10         | 0.06–0.09 kg                   | Best in class today                          |

Source: ICCT (2020)

The Boeing 737-800 is the most produced aircraft in commercial aviation and as a result accounted for almost 15 percent of global commercial aviation emissions as of October 2022 (Graph 2). The Airbus A320 family is the primary competition for Boeing 737's. As of October 2022, the Airbus A320-200 accounted for 11.6 percent of aviation emissions.



Graph 2. Distribution of commercial aviation emissions worldwide in 2022, by aircraft type

Source: Authors' elaborations, data from Statista

Bernardo and Fageda (2025) estimated whether the fuel efficiency may be offset by supply growth. The authors found that the adoption of new aircraft has led to a substantial increase in supply that does, in part, offset the greater fuel efficiency. However, the evidence shows heterogeneous effects depending on the type of route or

geographical area analyzed. As a result, while modern aircraft are substantially more fuel-efficient than previous generations, achieving further large-scale improvements is becoming increasingly challenging and will likely require breakthrough technologies and alternative jet fuels as shows the next section.

### 3. Alternative jet fuels

#### 4.1 Sustainable aviation fuels

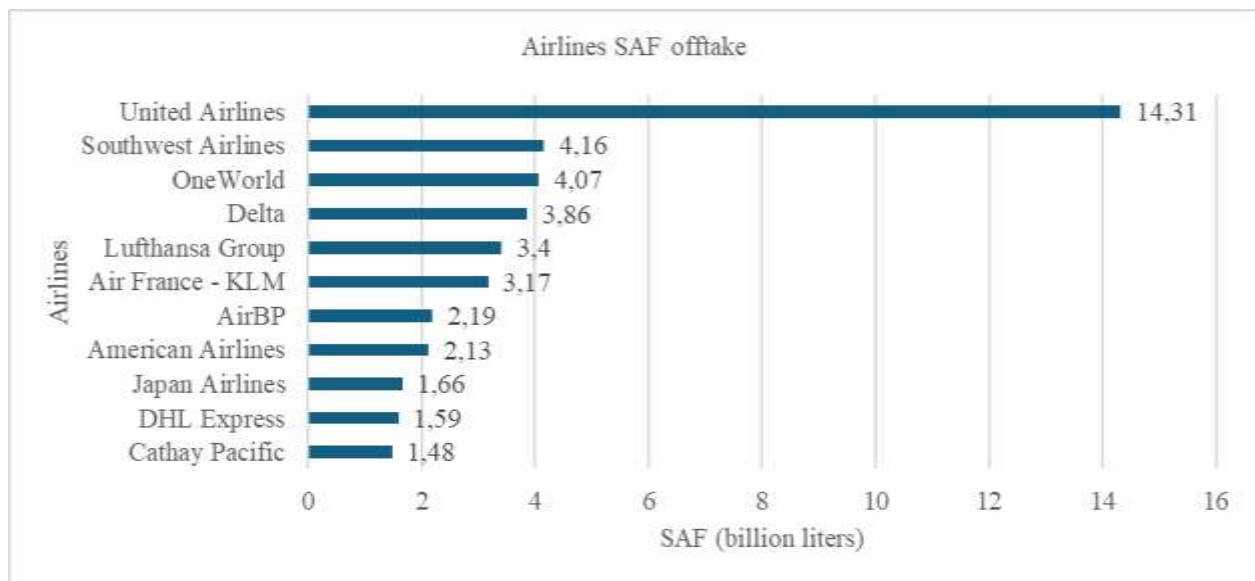
The aviation industry is pursuing a wide range of innovative approaches to reduce carbon emissions and achieve net-zero emissions by 2050. Sustainable Aviation Fuel (SAF) is a type of liquid fuel used in powering aircraft engines that can reduce the CO<sub>2</sub> emissions in the aviation industry by up to 80 percent (IATA, n.d.). SAF can be produced by different methods such as hydroprocessed esters and fatty acids (HEFA) conversion, advanced biomass to liquid fuels such as Fischer–Tropsch (FT) and alcohol-to-jet process (ATJ), pyrolysis, and power-to-liquid (PtL) fuels from renewable H<sub>2</sub> and CO<sub>2</sub> (Detsios et al., 2023).

One of the most critical barriers to SAF adoption is its high-cost relative to conventional jet fuel. This cost burden is particularly significant in an industry characterized by thin profit margins and intense competition<sup>3</sup>. On average, SAF is currently priced between two and five times higher than fossil-based jet fuel, although this premium can be even greater depending on the production pathway. As an example, the typical SAF prices in 2025 ranged from approximately \$5 to \$7 per gallon (BloombergNEF, 2026), compared to \$1.93 to \$2.39 per gallon for conventional jet fuel (Eurocontrol, 2025). Regional variations in SAF pricing also exist, reflecting differences in policy support, feedstock availability, and production infrastructure. These cost differentials influence airline adoption decisions and highlight the importance of consistent global policy frameworks. The economic impact of SAF adoption is already becoming visible. While SAF in 2026 is expected to represent 0.8 percent of the global aviation jet fuel consumption with an average price of \$2,872 per tonne, its use is expected to add \$4.3 billion to additional fuel costs for airlines in 2026 (IATA, 2026-c). Pricing methodologies provide insight into the current market pricing, however, true cost transparency is still lacking and the accurate financial risk faced by airlines remains unclear (IATA, 2024).

Since 2013, United Airlines has purchased more sustainable aviation fuels (SAF) than the other global airlines, with an offtake volume of more than 14.3 billion liters. Southwest Airlines ranked second with a total offtake volume of over 4.16 billion liters of SAF (Graph 3). As a result, widespread adoption of SAF without policy support or cost reductions remains financially challenging. For instance, financial incentives in the United States can provide up to \$1.75 per gallon in tax credits (U.S. Department of Energy, n.d.).

Looking ahead, there is cautious optimism regarding the future cost trajectory of SAF. As production scales up and technologies mature, costs are expected to decline. HEFA-based SAF may approach cost parity with conventional jet fuel by the early 2030s, particularly with continued policy support. If facilities that are currently under construction are taken into account, the amount of SAF production capacity in 2030 could reach 3.51 million tonnes (Mt). This could be considered a ‘realistic scenario’. Again, almost all this production would be dominated by the HEFA production pathway and does not include any PtL production, as no plant has yet evolved beyond a pilot stage (EASA, n.d.-c). As of September 2026, the most affordable SAF remains fuel produced via the HEFA pathway, averaging \$1,817 per tonne. Advanced bio-SAF made from waste feedstocks averaged \$3,399 tonne, while synthetic e-SAF, produced from hydrogen and carbon dioxide, averaged \$5,015 per tonne, nearly seven times the price of conventional jet fuel (UkrAgroConsult, 2026).

<sup>3</sup> Airlines’ net profit margin in 2025 was 3.9% (IATA, 2025-b).



Graph 3. Aviation industry main purchasers of SAF (in billion liters) 2013-2026

Source: Authors' elaborations, data from Statista

Several additional structural barriers further constrain SAF expansion. Global SAF production remains limited relative to total aviation fuel demand. Feedstock availability is a major limitation, as current SAF production relies heavily on waste oils, used cooking oil, and agricultural residues. These resources are finite and also in demand from other industries, such as biodiesel production. By 2025, worldwide production is expected to reach approximately 2 million tonnes, equivalent to about 600 million gallons. This represents less than 1 percent of total jet fuel consumption, underscoring the early stage of market development. Although production capacity is expanding rapidly with expectations that output could double in the near term, the gap between supply and demand remains considerable, with demand estimated to be several times higher than current production levels. Even under optimistic scenarios, SAF is projected to account for only about 10 percent of global aviation fuel consumption within the next decade, indicating the scale of the challenge in achieving meaningful use (World Economic Forum, 2021). Additionally, infrastructure constraints pose challenges, as only a limited number of airports worldwide currently have the capability to supply SAF through existing fuel distribution systems (ICAO, n.d.-e). Transportation and logistics costs further increase the overall price of SAF, adding additional financial pressure.

The CADO SAF registry was launched in 2025 to help solve the challenge of limited SAF supply. It is a global system to record SAF transactions in a standardized and transparent way by connecting airlines with SAF producers and suppliers providing book and claim solution regardless of their geographical location (CADO, n.d., IATA, 2025-a). Furthermore, policy support plays a critical role in addressing these challenges. Governments have introduced various incentives, including tax credits, subsidies, and blending mandates, to stimulate SAF production and adoption. The ReFuelEU Aviation Regulation framework in Europe started with 2 percent SAF mandate in 2025 and will increase to 70 percent in 2050 (EASA, n.d.-a). Instead, in the United Kingdom SAF mandate initiated with 2 percent in 2025 and will extend to 22 percent in 2040 (Gov.uk, 2024).

Carbon pricing mechanisms and emissions trading systems contribute by internalizing the environmental cost of conventional jet fuel, thereby improving the relative competitiveness of SAF. In 2016, The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is the first global market-based scheme that applies to a sector. When started CORSIA had 88 member states and increased to 130 in 2026 (ICAO, n.d.-b). It is estimated that by 2050, using SAF in the aviation industry will reach 65 percent of the total fuel requirement and a production of 449 billion liters. The scenario is based on appropriate government policy support and use of clean technology (IATA, n.d.).

In conclusion, while SAF represents one of the most promising pathways for reducing aviation emissions in the near to medium term, its widespread adoption is constrained by high costs ranging 120-170 percent higher than fossil-based jet fuel costs, limited production capacity, and lack of producers' incentives (Watson et al., 2024). Overcoming these barriers will require coordinated efforts across governments, industry stakeholders, and technology developers.

## 4.2 Future propulsion technologies

In parallel with the development of SAF, the future of aircraft propulsion technologies is evolving toward transformative, low- and zero-emission solutions. While SAF provides an immediate and compatible pathway for reducing emissions in existing fleets, long-term decarbonization will depend fundamentally on new propulsion systems. Airlines, aircraft manufacturers, and researchers are focusing on developing cleaner and more fuel-efficient technologies to minimize the environmental impact of air transport. The following are some of the most promising attempts and emerging technologies that could significantly contribute to reducing aviation-related carbon emissions in the future.

### 4.2.1 Hydrogen

Table 2 presents a comparison hydrogen and conventional jet fuel. Hydrogen propulsion is considered one of the most promising options for medium- to long-term decarbonization because it can eliminate carbon dioxide emissions at the point of use (Farokhi, 2025). Hydrogen can be utilized through two primary pathways: direct combustion in modified gas turbine engines or conversion into electricity via fuel cells. Hydrogen combustion systems offer efficiencies comparable to or slightly higher than conventional jet engines, typically in the range of 35–45 percent. In contrast, hydrogen fuel cell systems are significantly more efficient, achieving efficiencies of approximately 45–60 percent. Fuel cells generate electricity to power electric motors, offering a cleaner and more efficient alternative, particularly for smaller aircraft and short-haul operations.

In terms of environmental performance, hydrogen offers a critical advantage: it produces zero CO<sub>2</sub> emissions during operation. Additionally, it generates negligible particulate matter and significantly lower nitrogen oxide (NO<sub>x</sub>) emissions compared to conventional jet fuel, particularly when used in fuel cell systems. This makes hydrogen a highly attractive option for achieving deep decarbonization in aviation. However, it is important to note that lifecycle emissions depend on how the hydrogen is produced. “Green hydrogen” generated using renewable energy, provides the greatest environmental benefit, while hydrogen produced from fossil fuels without carbon capture offers limited emissions reduction.

Widespread adoption requires significant advances in storage, infrastructure, and aircraft design including the integration of cryogenic fuel storage systems, as well as the development of new airport infrastructure for hydrogen production, storage, and distribution (Öztürk and Yıldız, 2026). Hydrogen’s low volumetric energy density presents a major engineering challenge. Even in liquid form, hydrogen requires approximately four times more storage volume than jet fuel. In some aircraft design scenarios, the required volume can increase by as much as 260 to 900 percent, depending on range and configuration. As a result, hydrogen-powered aircraft must be fundamentally redesigned to accommodate larger fuel tanks, often requiring new fuselage configurations such as blended-wing bodies or modified cylindrical structures. These design changes can also lead to increased aerodynamic drag, in some cases by 27–67 percent, partially offsetting the efficiency gains achieved through lower fuel weight. Hydrogen must also be stored at extremely low temperatures, approximately –253°C, in order to remain in liquid form. This cryogenic storage requirement introduces additional complexity in aircraft design, insulation systems, and airport fueling infrastructure. Maintaining such low temperatures safely and efficiently during flight operations is a major technical challenge that has yet to be fully resolved at a commercial scale.

In terms of operational capability, early hydrogen-powered aircraft are expected to be limited to short- and medium-haul routes. Current conceptual designs suggest that hydrogen aircraft could carry approximately 100 passengers over distances of around 1,000 nautical miles (approximately 1,850 kilometers). This makes hydrogen most suitable for regional aviation in its initial stages of deployment, with potential expansion to larger aircraft and longer routes as technology advances. Safety considerations also play a critical role in hydrogen adoption. Hydrogen has a wide flammability range (approximately 4 to 75 percent in air) and requires very low ignition energy, necessitating advanced safety systems and strict regulatory standards. However, with proper engineering and safety protocols, these risks can be effectively managed, as demonstrated in other industries that already utilize hydrogen.

Economic factors represent another major barrier to hydrogen adoption. Currently, the cost of liquid hydrogen ranges from approximately \$6 to \$11 per kilogram, compared to roughly \$1.5 to \$3 per kilogram for conventional jet fuel. This implies that hydrogen is about two to four times more expensive than traditional aviation fuels. In addition to fuel costs, significant capital investment is required to develop hydrogen production facilities, storage systems, and airport refueling infrastructure. These economic challenges must be addressed through technological innovation, economies of scale, and supportive policy frameworks.

To fully leverage the potential of hydrogen-electric propulsion, Beyond Aero has adopted a clean-sheet design philosophy – developing its aircraft from the ground up around the unique architecture and requirements of this next-generation power source (World Economic Forum, 2025). The first electric aircraft powered by hydrogen

propulsion is designed to carry six passengers up to 800 nautical miles (1,500km) – five times farther than similar battery-electric aircraft (World Economic Forum, 2025).

In comparison to alternative energy sources such as batteries, hydrogen offers a clear advantage for aviation applications. Battery energy density is currently only about 5–8 percent that of jet fuel, making fully electric aircraft impractical for anything beyond very short-range operations. Hydrogen, therefore, represents a more viable pathway for achieving zero-emission flight, particularly for larger aircraft and longer distances. Hydrogen holds significant promise as a future aviation fuel due to its high energy density, zero carbon emissions at the point of use, and potential for high propulsion efficiency. Business aviation is the low hanging fruit of the aviation world, and is likely to be the first to see a shift towards hydrogen due to its less costly aircraft certification process, operational fit with more than 70 percent of flights under 1,000 km and low maintenance requirements (World Economic Forum, 2025). Continued research, investment, and policy support will be essential to overcome the challenges and unlock its full potential and enable a transition toward sustainable, zero-emission air transport.

Table 2. Key technical and economic parameters of hydrogen in aviation

| Category                       | Hydrogen (H <sub>2</sub> )                                 | Conventional Jet Fuel (Jet A-1) | Implications for Aviation                                            |
|--------------------------------|------------------------------------------------------------|---------------------------------|----------------------------------------------------------------------|
| Energy Density (mass)          | 120 MJ/kg                                                  | 43 MJ/kg                        | Hydrogen has 3× higher energy per unit mass                          |
| Energy Density (volume)        | Very low (liquid H <sub>2</sub> 4× larger volume required) | High                            | Requires much larger fuel tanks and redesigned aircraft              |
| Fuel Storage Temperature       | 253°C (cryogenic)                                          | Ambient conditions              | Requires complex insulation and airport infrastructure               |
| CO <sub>2</sub> Emissions      | 0 (point of use)                                           | High                            | Enables zero-emission flight when using green hydrogen               |
| NO <sub>x</sub> Emissions      | Very low (fuel cells near zero)                            | Significant                     | Major reduction in local air pollution                               |
| Propulsion Efficiency          | Fuel cell: 45–60%<br>Combustion: 35–45%                    | 38–42%                          | Potential efficiency improvement, especially with fuel cells         |
| Fuel Cost (2025 est.)          | \$6–11 per kg                                              | \$1.5–3 per kg                  | Hydrogen is 2–4× more expensive                                      |
| Aircraft Range (early designs) | 1,000 nautical miles (1,850 km)                            | 3,000–8,000+ km typical         | Initially limited to short/medium-haul routes                        |
| Fuel Weight Impact             | 50–60% reduction                                           | Baseline                        | Significant reduction in takeoff weight                              |
| Aircraft Design Impact         | Requires new fuselage/tank integration                     | Conventional design             | Likely shift to new aircraft architectures (e.g., blended wing body) |
| Infrastructure Readiness       | Very limited                                               | Fully developed global network  | Major investment needed in airports and supply chains                |

Source: Gopalasingam et al. (2025), Airbus (2022)

#### 4.2.2 *Electric and hybrid-electric aircraft*

Electric propulsion is another key area of development and represents a transformative pathway, particularly for short-haul aviation. Jet fuel delivers approximately 12,000 Wh/kg of energy significantly more than today's best batteries, which achieve around 259 Wh/kg. This fundamental limitation currently restricts battery-electric aircraft to subregional missions and light payloads (World Economic Forum, 2025; ATAG, 2010). Ongoing advancements in battery technology are expected to gradually extend the feasible range of electric aircraft.

Hybrid-electric systems provide a transitional solution by combining conventional engines with electric power to improve efficiency and reduce emissions (Dai et al., 2025). Electric and Hybrid Aircraft Platform for Innovation (E-HAPI) is a non-extensive list of ongoing projects that have been identified globally, ranging from general aviation or recreational aircraft, business and regional aircraft and large commercial aircraft (ICAO, n.d.-d). A brief description is shown below about the projects included in each category. The general aviation/recreational aircraft group consists of aircraft with MTOW from 300 to 1000 kg. These are mostly electric powered aircraft with a seat capacity of two passengers which are already produced and certified. The aircraft under the business and regional aircraft category includes longer flight range close to 1000 km with seat capacity of about ten passengers. The large commercial aircraft category includes initiatives focused on hybrid-electric, single-aisle aircraft with seat capacities of 100-135 and targeted entry into service after 2030 (ICAO, n.d.-d).

The use of a hybrid power plan contributes to an average reduction of fuel consumption by 10 percent, NO<sub>x</sub> emissions by 25 percent, water vapor emissions by 10 percent, and CO<sub>2</sub> by 10 percent (Synylo et al., 2024). Additionally, Gimenez et al. (2023) compared a reference aircraft with other more-electric and hybrid-electric versions of the same type. The authors confirmed that the hybrid powertrain has better results. The least efficient hybrid configuration reduced fuel consumption by 10.7 percent in the conventional aircraft and by 1 percent in the battery-powered more-electric type. Considering the actual low density of batteries available on the market, long-range hybrid-electric aircraft will require substantial time to become viable. Cusati et al. (2025) evaluates the direct operating costs (DOC) and economic feasibility of the Ampaire Eco Caravan, a hybrid-electric retrofit of the Cessna 208B Grand Caravan. The results show that the Eco Caravan reduces fuel consumption by 50 percent due to its hybrid-electric propulsion system. Additionally, maintenance costs decrease by 14 percent, and for a 100-nautical-mile mission, operational costs are 9 percent lower than the conventional model. However, higher acquisition costs and reduced block speed increase total DOC by 3 percent. These findings suggest hybrid-electric aircraft can be viable with technological advancements and regulatory support.

Nakano et al. (2022) found that the introduction of electric aircraft, hydrogen-powered aircraft and synthetic fuel into the aviation sector would contribute to the cost-effective achievement of emissions reductions in line with Paris goals. For achieving less than 2 degrees Celsius with more than 66 percent probability, the introduction of electric- and hydrogen-powered aircraft, and synthetic fuel would decrease costs by \$2,743 billion and \$135 billion per year in 2100, respectively. As a result, electrification can help to reduce the carbon footprint of aviation (Hou et al., 2023). Nevertheless, Liang et al. (2024) show the substantial power demand associated with the charging process, emphasizing the essential infrastructure needs and potential approaches for managing charging power in electric flight. Smart charging and minor modifications to flight schedules can substantially reduce peak power demands, and in turn the needs for grid infrastructure upgrade (Hou et al., 2023). Furthermore, plug-in charging of future electric aircraft will lead to elevated fluctuations in electric power demand at airports, while battery swapping has a more constant electricity demand (Lindberg and Leijon, 2025). More research is needed regarding the optimal configuration of airport infrastructure to support electric aircraft development (Lindberg and Leijon, 2025).

## 5. Conclusion

Balancing environmental sustainability with continued growth in air travel demand presents an ongoing challenge. As global connectivity expands, emissions reduction efforts must outpace demand growth to achieve meaningful progress. In the current decade between 2020 and 2030, SAF plays a key role for the emissions of existing fleets while hydrogen-electric systems take off (World Economic Forum, 2025). The scalability of SAF remains a critical barrier. Current production levels are insufficient, and expanding supply requires large-scale investment, stable policy frameworks, and sustainable feedstock availability. The high SAF cost poses economic challenges for airlines operating in a highly competitive market. Without consistent global policies and financial incentives, widespread adoption may be delayed. Technological uncertainty remains a key issue. While hydrogen and electric propulsion show promise, their commercial viability especially for long-haul flights has yet to be proven at scale. Infrastructure limitations present a major obstacle, for these technologies. Airports, fuel supply chains, and aircraft designs must undergo significant transformation to accommodate these technologies.

During 2030-2040, advances in fuel cell performance and liquid hydrogen storage technologies, will support the development of regional aircraft certified validating hydrogen-electric systems on higher-capacity routes and expanding their relevance across regional markets (World Economic Forum, 2025). By 2040 to 2050, the decarbonization roadmap will enter its consolidation phase, aimed at launching a 150-seat commercial aircraft equipped with scaled hydrogen systems. This will unlock the ability to target high-frequency, short-haul routes that currently account for up to 24% of aviation-related emissions. Addressing these segments positions hydrogen-electric propulsion as a credible, high-impact alternative to conventional jet fuels (World Economic Forum, 2025).

Overall, the future of aviation propulsion is characterized by a multi-technology transition. SAF will dominate the near-term decarbonization strategy, while hydrogen and electric propulsion systems will gradually reshape the industry over the longer term. Achieving this transition will require coordinated investment, technological innovation, and global policy alignment.

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