

# 1 Introduction

Sustainable aviation aims to achieve net-zero carbon emissions by 2050. Climate change, rising fuel costs, and increasing regulatory pressure all act as major motivators for this initiative. Unlike many other sectors, aviation presents unique challenges due to its stringent safety and certification requirements, high energy-density demands, and limited tolerance for additional system mass. In particular, commercial aviation features some of the longest operational ranges of any transport mode, placing severe constraints on the feasibility of low-carbon energy storage and propulsion technologies. Nevertheless, when sustainable changes are implemented effectively on long-haul flights, even modest improvements can accumulate over time and deliver substantial environmental and economic benefits.

This essay is structured as follows. First, advances in fuel systems are examined, highlighting both their potential and limitations. Next, developments in aircraft design and operational strategies aimed at improving efficiency are discussed. Finally, the socio-economic impacts of these changes are explored. Ultimately, it is argued that, rather than relying primarily on novel fuel systems, commercial aviation is more likely to realise a sustainable future by 2055 through unconventional aircraft designs, improved operational efficiency, and incremental changes whose effects compound over long-distance operations.

## 2 Advances in Fuel

Traditionally, jet fuels are kerosene-based. Among all contributors to greenhouse gas (GHG) emissions in today's commercial aviation sector, the energy systems used to power aircraft represent the largest share (Afonso et al., 2023). In 2019, aviation accounted for approximately 2.5% of global GHG emissions (Ritchie, 2024). As demand for air travel continues to grow, and given the industry's inherently slow rate of change due to stringent certification requirements, aviation's contribution to global warming is expected to increase without significant intervention. Three promising technological pathways for carbon emissions reduction have emerged: sustainable aviation fuels (SAFs), and battery-electric propulsion and hydrogen-based propulsion systems, each offering a distinct balance between technical feasibility and scalability.

SAFs are likely to provide the main lever for near-term emissions reduction up to 2055, because they can be used in existing aircraft and infrastructure, but their long-term scalability is constrained by feedstock availability. SAFs are renewable liquid fuels produced from biomass, organic waste, or direct air carbon capture (Wang et al., 2024). Owing to their compatibility with current aircraft and airport systems (Wang et al., 2024), they enable near-term adoption without major airframe or propulsion system redesign. On a lifecycle basis, SAFs have the potential to reduce GHG emissions by up to 80%, depending on feedstock and production pathway (Capaz et al., 2021).

While large-scale deployment of SAFs could, in principle, achieve substantial reductions in CO<sub>2</sub> emissions based on projected biomass availability (Wei et al., 2019), limited sustainable feedstock presents a significant constraint. Despite the existence of multiple production pathways, such as those based on fats, oils, and sugars, current and foreseeable SAF production capacity is unable to meet global aviation fuel demand (Lohawala and Wen, 2024). Furthermore, extensive investment in SAF research and infrastructure risks diminishing economic returns if overall supply remains capped. Consequently, direct replacement of conventional jet fuel with SAFs is best viewed as a near- to medium-term mitigation strategy, rather than a fully scalable long-term solution for commercial aviation.

Alternatively, battery-electric propulsion presents a fundamentally different pathway towards emissions reduction. Electric aircraft produce zero in-flight emissions and benefit from lower maintenance requirements due to reduced mechanical complexity (Sarlioglu and Morris, 2015). However, their application to commercial aviation is severely constrained by the low energy density of current battery technologies. As a result, large-scale adoption of battery-electric propulsion in long-haul commercial aviation remains unlikely in the near- to medium-term. Nevertheless, electrification

shows considerable promise within private aviation, short-range regional transport, and urban air mobility, where flight durations and payload requirements are significantly reduced. In the longer term, emerging concepts such as structural batteries may partially alleviate mass penalties, though their practical integration into certified aircraft structures remains an open research challenge (Greenhalgh et al., 2023).

Hydrogen-based propulsion is widely regarded as the most credible long-term zero carbon option for larger aircraft, but only if substantial breakthroughs in storage, infrastructure, and certification are achieved. Hydrogen-based propulsion presents a promising long-term solution for reducing carbon emissions in aviation, as hydrogen contains no carbon and therefore produces no CO<sub>2</sub> at the point of use (Raihan, 2025). Hydrogen can be utilised either through direct combustion in modified gas turbines or via fuel cells coupled with electric propulsion systems.

While hydrogen fuel cells offer high efficiency and zero carbon emissions, it is important to note the persistence of non-CO<sub>2</sub> effects. These include contrail formation and, in the case of hydrogen combustion, nitrogen oxide emissions, both of which may continue to contribute to global warming if not carefully managed (Afonso et al., 2023).

Despite its promise, the application of hydrogen propulsion to passenger-carrying commercial aircraft presents significant technical challenges. Hydrogen's low volumetric energy density means that large cryogenic storage tanks are required and this imposes penalties on aircraft mass, internal volume, and aerodynamic efficiency (Raihan, 2025). Furthermore, the storage, distribution, and certification of hydrogen systems remain major barriers to commercial adoption. Nevertheless, hydrogen-powered aircraft are not a novel concept. Ongoing demonstrator programmes, such as the Airbus's ZeroE and ZeroAvia's ZA600, indicate that hydrogen propulsion is being pushed higher up in technological readiness, reinforcing its position as a viable long-term solution for sustainable commercial aviation.

No single fuel or propulsion technology alone provides a complete or immediately scalable solution for the decarbonisation of commercial aviation, particularly on long-haul routes. This naturally points towards hybridisation, in which multiple energy systems are combined to exploit their complementary strengths and mitigate individual limitations.

By 2055, commercial aviation is likely to adopt hybrid configurations that integrate SAFs with hydrogen-based systems, balancing near-term compatibility with longer-term emissions reduction. Further into the future, hybrid-electric aircraft incorporating advanced energy storage technologies, such as structural batteries, may offer the greatest potential to mitigate aviation's environmental

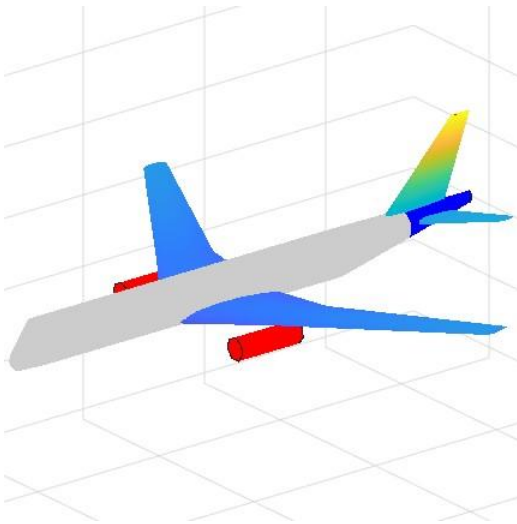
impact, provided that challenges related to safety, certification, and infrastructure are successfully addressed. For the remainder of this essay, future aircraft are assumed to employ a hybrid SAF-hydrogen propulsion system.

### 3 Advances in Design

To accommodate hybrid propulsion architectures and achieve greater reductions in environmental impact, commercial aviation will likely require new and unconventional aircraft configurations. Over recent decades, conventional tube-and-wing designs have been extensively optimised, reaching a point where further incremental improvements yield diminishing returns in aerodynamic efficiency and fuel burn (Abbas et al., 2013a). Since fuel burn is strongly correlated with aerodynamic drag, maximising aerodynamic efficiency has become one of the driving design factors for reducing emissions (Mohamed-Kassim and Filippone, 2010). Recent developments, such as high aspect-ratio wings on the Airbus A350 (Strüber, 2014), illustrate the continued pursuit of efficiency within this paradigm; however, such approaches are increasingly constrained by the architecture's limits.

While several unconventional aircraft configurations have been proposed, their feasibility depends strongly on regulatory certification challenges, infrastructure compatibility, and economic viability. Among these concepts, the blended wing body (BWB) configuration offers particularly high potential for maximising aerodynamic efficiency and allowing for integration with hydrogen propulsion systems (Wang et al., 2024).

BWB integrates the fuselage and wings into a single lifting surface (Liebeck, 2004), in contrast to the conventional tube-and-wing layout. This results in a significant reduction in wetted area and interference drag, leading to substantially higher lift-to-drag ratios compared to conventional aircraft (Liebeck, 2004). Studies have shown that BWB aircraft can achieve 27% reduction in fuel burn per seat relative to equivalent tube-and-wing designs (Liebeck, 2004; Martinez-Val et al., 2010). In addition to aerodynamic benefits, the large internal volume of the BWB provides greater flexibility for the integration of hydrogen fuel cells or distributed electric propulsion. Furthermore, BWBs can simultaneously address fuel burn, emissions, and noise objectives; in particular, top-mounted engines benefit from airframe shielding, which reduces perceived community noise (Zhenli et al., 2019).



(a) Conventional Tube and Wing design, made during my AVD project



(b) Exemplar BWB, Boeing/NASA's X48

Figure 1: Comparison between recent and prospective configurations

Despite these advantages, the BWB configuration presents several challenges. As illustrated in Figure 2, the BWB strongly prioritises aerodynamic performance, often at the expense of other disciplinary considerations. This leads to increased structural complexity and concerns related stability and control, and passenger acceptance. In addition, the absence of a conventional cylindrical fuselage complicates structural load paths and certification under existing regulatory frameworks (Mohaghegh, 2005). As a result, despite their compelling theoretical performance advantages, large-scale adoption of BWB aircraft is unlikely in the near term.

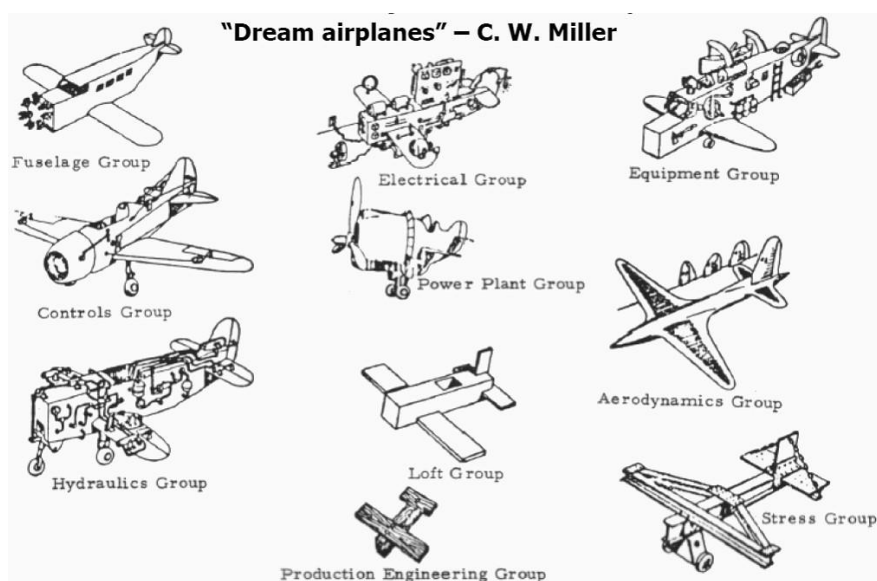


Figure 2: "Dream Airplanes" (Nicolai and Carichner, 2010), illustrating the consequences of only considering one design aspect when designing an aircraft

From a commercial and operational perspective, stability represents one of the most significant barriers. The BWB exhibits inherent dynamic instabilities, particularly in Dutch roll and spiral modes (Lixin et al., 2022). Although modern control strategies, such as incremental nonlinear dynamic inversion, have demonstrated substantial improvements in handling qualities (van Overeem et al., 2023), BWB aircraft inevitably rely on continuous active flight control for stability. While such reliance is technically feasible, it introduces certification, redundancy, and passenger-confidence challenges that remain difficult to justify for near-term commercial service.

Consequently, a compromise between aerodynamic efficiency and stability becomes necessary. One such compromise is the hybrid wing body (HWB) configuration, investigated in 2009 by Lockheed Martin. The HWB retains many aerodynamic advantages of the BWB while incorporating a conventional T-tail, improving static and dynamic stability and easing certification challenges. In this sense, the HWB represents an intermediate configuration that amalgamates favourable characteristics of both tube-and-wing and BWB architectures. Similarly, Airbus' MAVERIC concept demonstrates how geometric tailoring and control integration can be used to mitigate inherent stability issues while preserving aerodynamic gains. Nonetheless, multidisciplinary design optimisation would be required to further optimise each of these configurations (Okonkwo and Smith, 2016).



(a) Lockheed Martin's novel HBW configuration (Petrescu et al., 2018)

Figure 3: Comparison between recent and prospective configurations

In the near term, alternative approaches may offer a more practical pathway to sustainability. For long-haul flights, even modest improvements in aerodynamic efficiency accumulate over extended flight durations, resulting in substantial reductions in fuel consumption and emissions. Accordingly, recent design enhancements such as laminar flow control and boundary-layer ingestion have received

increased attention (Abbas et al., 2013*b*). These technologies bring performance gains without the structural and certification complexity associated with radically unconventional aircraft, offering a feasible compromise while retaining much of the aerodynamic benefit.

To conclude this section, future commercial aircraft are more likely to emerge from balanced design trade-offs that selectively incorporate unconventional features within configurations compatible with existing regulatory and operational frameworks. Intermediate configurations, such as HWBs, combined with design enhancements provide a more credible pathway to meaningful emissions reduction when paired with hybrid propulsion systems.

## 4 Advances in Sustainability

The prospect of adopting unconventional aircraft configurations and hybrid propulsion architectures has driven significant advances in sustainability across materials, manufacturing processes, and aircraft operations.

Maximising aerodynamic efficiency is not the sole means of reducing fuel burn. Modern aircraft have been increasingly relying on lightweight composite materials, particularly carbonfibre-reinforced polymers (CFRPs), to reduce structural mass and allow for more payload capacity. For example, the Airbus A350 boasts a 53% composite materials by weight in its primary structure (Kesarwani et al., 2017). Beyond weight reduction, composites also offer a smaller environment impact during operation when compared directly to metals (Vieira and Bravo, 2016). However, the sustainability of composite materials is not without its limitations. The production of CFRP components, particularly those cured using autoclave-based processes, is energy intensive. In response, efforts have focused on the development of advanced metallic alloys, such as high-performance titanium and nickel-based superalloys (Huang et al., 2016), which offer improved strength-to-weight ratios, recyclability, and compatibility with lower-energy manufacturing techniques. These materials provide a complementary pathway to sustainability, particularly in primary structures or high-temperature regions of the aircraft.

Manufacturing processes have also been developed to support these advanced materials. In particular, metal additive manufacturing (AM) enables the production of highly complex, topology-optimised metal components that minimise material usage while maintaining structural performance. Compared to conventional subtractive manufacturing, AM reduces material waste, shortens supply chains, and lowers energy consumption during production (Wong and Hernandez, 2012). Combining additively manufactured components with composites enable more efficient structural architectures

while reducing the overall environmental footprint of aircraft manufacturing. For instance, the Hyperjoint concept demonstrates how hybrid metal/composite joints can achieve high structural efficiency while reducing weight and assembly complexity (Parkes et al., 2014).

Operational sustainability is further enhanced through advances in maintenance strategies and flight path optimisation. The increasing deployment of structural health monitoring (SHM) systems enables condition-based and predictive maintenance by continuously tracking stress and fatigue in critical structural components (Boller, 2001). This not only minimises aircraft downtime, but improves operational safety and extends component service life, which all contribute to lower operational costs.

Flight path optimisation and scheduling are also important. Advanced trajectory planning, enabled by real-time weather data, performance modelling, and air traffic management coordination, allows aircraft to minimise fuel burn through optimised altitudes, speeds, and routing (Sridhar et al., 2011). These operational improvements can yield measurable reductions in emissions without requiring changes to airframe or propulsion systems, making them particularly attractive for near-term implementation. Studies have also shown that optimised flight paths have additional benefits of reducing the workload of air traffic controllers (Rosenow et al., 2019). Complementary improvements in ground traffic management further reduce fuel burn by minimising taxi times, holding delays, and congestion at airports.

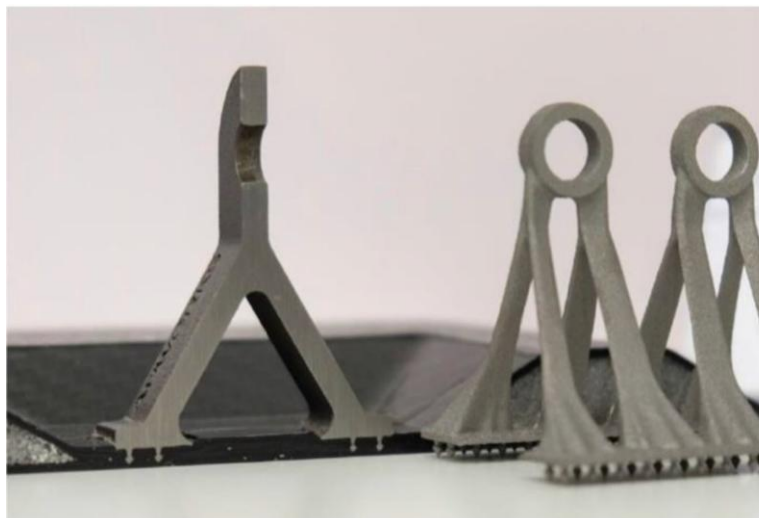


Figure 4: Airbus' Hyperjoint concept, an additive manufactured metal part is joint with a composite plate

Advances in materials, manufacturing processes, and operational technologies demonstrate that sustainability in aviation extends well beyond fuel and propulsion systems. Often overlooked, these

"behind-the-aircraft" technologies will play a critical role in achieving sustainable commercial aviation by 2055.

## 5 Socio-Economic Impact

The demand for air transport is expected to remain high, driven by tourism, trade, and migration. International Civil Aviation Organization predicts that global passenger demand is expected to approximately double by 2040, while the United Nations projects world population growth to nearly 9.7 billion by 2050. These trends imply a sustained increase in air travel demand (Grimme et al., 2021). As such, sustainable aviation must accommodate rising demand while simultaneously reducing its environmental footprint. The socio-economic impact of this transition can be discussed under three main themes: the economy, job opportunities, and operations.

The diversification of energy sources toward SAFs, hydrogen, and other low-carbon options can strengthen energy security by reducing exposure to oil price volatility and supply disruptions. This also supports new value chains in agriculture, waste management, and renewable energy. If we focus on SAFs, they currently remain more expensive than traditional jet fuel, with costs estimated at approximately 120% higher for the most mature production pathways (Watson et al., 2024). As a result, large-scale adoption may increase airline operating costs and exert upward pressure on ticket prices in the short to medium term, potentially dampening discretionary travel. In the bigger picture, however, sustainable aviation can still deliver net benefits by preserving global connectivity, enabling tourism and trade, and avoiding the long-term economic costs associated with climate change impacts and local air pollution.

Sustainable aviation generates employment well beyond traditional aircraft engineering roles. Scaling up SAF and hydrogen production requires expanded workforces across feedstock cultivation, fuel processing, logistics, certification, and quality assurance, creating employment opportunities in both rural and industrial regions; emerging aircraft concepts and propulsion architectures demand specialised expertise in aerodynamics, system integration and digital design tools, supporting high-skill engineering and manufacturing jobs over multiple decades of research, development, and test engineering.

Furthermore, airlines, airports and regulators increasingly require expertise in environmental policy, sustainability reporting, and climate-risk management. This opens new professional pathways in "green" aviation services. Legacy aircraft can also be repurposed as museum exhibits, educational platforms, or experimental test-beds for new technologies, supporting employment in heritage tourism, outreach, and applied research rather than immediate retirement.

As mentioned previously, airlines are increasingly focusing on more fuel-efficient aircraft operations, including optimised routing, continuous descent and climb procedures and advanced air traffic management systems that minimise down times (Rosenow et al., 2019). Airports contribute through more efficient ground operations, electrification of ground support equipment and better multimodal connections that encourage public transport access, all of which can reduce both emissions and operating costs over time while improving the passenger experience (Afonso et al., 2023). These operational changes can also have social benefits by reducing noise and local air pollutants around airports, which can improve public health in neighbouring communities (Santa et al., 2020).

## 6 Conclusion

Sustainable aviation is not achieved by a single technological breakthrough, but by the coordinated evolution of fuels, aircraft design and sustainability practices. While alternative fuels and novel propulsion concepts are essential for deep decarbonisation, equally important progress is being made through advanced materials, efficient manufacturing methods and operational improvements. The transition to sustainable aviation also carries significant socio-economic implications, reshaping employment, supply chains, and institutional expertise across the industry. New value chains in sustainable fuels, advanced manufacturing, and environmental governance create opportunities beyond traditional aerospace roles, while improved operations and infrastructure can deliver tangible local benefits in noise reduction, air quality, and public health.

Ultimately, achieving sustainable commercial aviation by 2055 will require a systems engineering approach that integrates technological innovation with operational efficiency and policy support. By addressing environmental performance alongside economic resilience and social impact, the aviation sector can remain a vital enabler of global connectivity while aligning with long-term sustainability goals.

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