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Advancing Sustainable Aviation Evaluating the Role of Alternative Fuels and Green Technologies in Reducing Carbon Emissions

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Abstract:
The aviation industry is a significant contributor to global greenhouse gas emissions, necessitating urgent strategies for carbon reduction to meet international climate targets. Sustainable aviation, driven by alternative fuels and green technologies, has emerged as a pivotal solution to mitigating environmental impacts. This study evaluates the potential of alternative fuels, such as sustainable aviation fuel (SAF), biofuels, and hydrogen-based fuels, in reducing carbon emissions while maintaining operational efficiency. It also examines advancements in green technologies, including electric and hybrid-electric propulsion systems, aerodynamic innovations, and lightweight composite materials, that collectively enhance fuel efficiency and minimize emissions. By analyzing recent developments and case studies from leading aviation companies, the study highlights both the opportunities and challenges associated with implementing these solutions on a large scale. The key barriers such as high production costs, infrastructure limitations, and regulatory constraints are critically assessed. Findings suggest that a combination of alternative fuels and green technologies can significantly reduce aviation's carbon footprint if supported by strong policy measures and industry-wide collaboration. This research underscores the need for continued investment, cross-sector partnerships, and innovation to achieve long-term sustainability goals, ultimately positioning the aviation sector as a leader in global efforts to combat climate change.

Keywords: Sustainable aviation, alternative fuels, green technologies, carbon emissions reduction, sustainable aviation fuel (SAF), hybrid-electric propulsion, climate change mitigation

1. Introduction:

The aviation sector is responsible for over 2% of global carbon dioxide emissions, with its share expected to rise as air travel demand grows (JetZero, 2025; IATA, 2025) — making decarbonization a critical industry priority. One key pathway is Sustainable Aviation Fuel (SAF), a bio-based or synthetic fuel that can reduce life-cycle emissions by up to 80–94%, depending on feedstock and production method (Ambrosio et al., 2025; U.S. Department of Energy) — while being fully compatible with existing aircraft and fueling infrastructure (Ambrosio et al., 2025). Despite recent growth, SAF remains a minor share of total aviation fuel. In 2025, production is projected to reach around 2 million tonnes, covering just 0.7% of global demand, and costing billions in premium price and compliance fees (Casey, 2025). Feedstock constraints—including reliance on oilseed crops and waste residues—along with high production costs, remain major barriers (Bonicontro Ambrosio et al., 2025; UNSW, 2025).

Alongside fuel innovations, green propulsion technologies are emerging. Hydrogen-electric aircraft—powered via fuel cells using cryogenically stored hydrogen—offer near-zero emissions at the tailpipe. Aircraft such as Germany's HY4 and ZeroAvia's HyFlyer have achieved piloted flights, demonstrating feasibility for regional aviation (DLR/H2Fly, 2023; ZeroAvia, 2025). Energy system modeling suggests that hydrogen-powered regional flights could reduce emissions by over 70%, with minimal payload penalties if fuel cell power density and tank gravimetric efficiency targets are met (Cybulsky et al., 2023; Sharma & Arief, 2024). Meanwhile, electric and hybrid-electric propulsion systems are being pursued for short-haul and advanced air mobility markets. U.S.-based companies like Beta Technologies recently completed the first landing of a passenger-carrying all-electric aircraft in dense airspace (Beta Technologies, 2025), and British developer Evolito is manufacturing axial-flux electric motors for hybrid retrofits in existing airframes (Evolito Ltd., 2025). JetZero's innovative blended-wing-body design may reduce aerodynamic drag and fuel use by up to 50%—offering tangible fuel savings without requiring entirely new infrastructure (JetZero, 2025).

These developments reflect two complementary decarbonization pathways: SAF offers an immediate, scalable emissions-reduction route, while hydrogen and electric aviation represent medium- to long-term technological transitions with transformational potential. Nonetheless, each pathway faces persistent challenges: SAF requires scale-up of supply chains and cost reduction; hydrogen and electric aviation need further advances in energy density, certification, infrastructure, and regulatory support. This study evaluates both alternatives—SAF and green propulsion technologies—through recent literature and industry case studies. It assesses technological readiness, economic feasibility, and policy mechanisms needed to accelerate adoption. By integrating evidence across fuels, propulsion systems, and market drivers, the research outlines actionable pathways for aviation to meet long-term emissions goals while maintaining safety, efficiency, and economic viability.

2. Background of Study:

The aviation industry is a cornerstone of global connectivity, contributing to economic growth and social development. However, it is also a significant source of greenhouse gas emissions, accounting for approximately 2.5% of global energy-related carbon dioxide (CO_2) emissions and around 4% of total climate impact when considering non-CO_2 effects such as contrails and nitrogen oxides (IEA, 2025; Our World in Data, 2024). Emissions from aviation have grown more rapidly than those from other transport modes because of increasing passenger demand and heavy reliance on fossil fuels (IEA, 2025). Without effective mitigation strategies, the sector's share of global emissions is expected to rise further, making decarbonization a critical priority.

Sustainable Aviation Fuels (SAF) have emerged as the most viable near-term pathway for emissions reduction, capable of cutting lifecycle CO_2 by 60%–98%, depending on feedstock and production processes (Bonicontro Ambrosio et al., 2025). SAF is compatible with existing aircraft and airport fueling infrastructure, making it easier to scale compared to alternative technologies (Earth.Org, 2024). However, production remains limited; global output in 2024 reached only 1.3 billion liters, representing about 0.3% of global jet fuel demand, largely because of high costs and limited feedstock availability (IEA, 2025).

The adoption of SAF is further constrained by its price, which is two to four times higher than conventional jet fuel (Earth.Org, 2024). Policy support, including low-carbon fuel standards, tax credits, and investment in feedstock supply chains, is crucial for accelerating production (New Yorker, 2023). Governments and industry coalitions are initiating collaborative efforts; for example, California has partnered with Airlines for America to scale SAF production to 200 million gallons annually by 2035, targeting 40% of intrastate travel demand. Despite these initiatives, significant gaps remain in achieving large-scale adoption at competitive prices.
Green propulsion technologies such as hydrogen and electric aircraft are being explored for medium- to long-term decarbonization. Hydrogen-powered regional aircraft like HY4 and HyFlyer prototypes have demonstrated potential emissions reductions of up to 70%, contingent upon advancements in fuel cell power density and hydrogen tank efficiency (Cybulsky et al., 2023; Sharma & Arief, 2024). Electric propulsion systems, targeted mainly at short-haul flights, are also progressing through initiatives like Europe’s Clean Aviation Programme, which seeks to achieve ≥80% CO_2 reductions by 2050 (Clean Sky Joint Undertaking, 2024). These technologies, however, require significant breakthroughs in energy density, infrastructure, and certification processes before large-scale implementation becomes feasible (Zubi et al., 2024).

This dual focus on SAF and green propulsion technologies represents a holistic approach to decarbonizing aviation. SAF offers an immediate and scalable method for reducing emissions in existing fleets, while hydrogen and electric technologies promise transformational long-term change (Our World in Data, 2024). Effective progress will require coordinated efforts from governments, airlines, manufacturers, and fuel producers to overcome economic, technical, and regulatory barriers. This background sets the context for evaluating how alternative fuels and green technologies can contribute to the aviation sector’s net-zero emissions targets by 2050.

3. Scope and Significance of Study

The scope of this study centers on evaluating the potential of alternative fuels and green propulsion technologies to reduce the aviation industry’s carbon emissions. The analysis is global in nature, considering leading initiatives from Europe, North America, Asia, and the Middle East, where governments and aviation stakeholders are aggressively pursuing decarbonization strategies (IEA, 2025). The study specifically addresses the production, scalability, cost implications, and technical feasibility of Sustainable Aviation Fuels (SAF) and emerging technologies such as hydrogen fuel cell-powered aircraft and electric propulsion systems. By examining both short-term and long-term solutions, it provides a holistic understanding of how these innovations can contribute to achieving aviation’s net-zero targets by 2050 (Clean Sky Joint Undertaking, 2024; Sharma & Arief, 2024).

The significance of this study lies in its emphasis on SAF adoption as the most immediately scalable solution for emissions reduction. While SAF can reduce lifecycle CO_2 emissions by up to 98%, its global production capacity remains under 1% of total jet fuel demand (Bonicontro Ambrosio et al., 2025; Earth.Org, 2024). Understanding the challenges of SAF supply chain development, feedstock availability, and cost competitiveness is critical to accelerating its deployment at scale. The study highlights policy tools such as carbon pricing, low-carbon fuel standards, and tax incentives that can drive investment and bridge the price gap with conventional jet fuel (AP News, 2024; New Yorker, 2023).

This research also underscores the strategic significance of hydrogen-powered and electric aircraft technologies, which are projected to play a transformative role in medium- to long-term decarbonization. Prototypes like ZeroAvia's HyFlyer and the HY4 aircraft demonstrate the feasibility of hydrogen fuel cells for regional flights, potentially reducing emissions by up to 70% (Cybulsky et al., 2023; Zubi et al., 2024). Electric propulsion, meanwhile, offers an avenue for zero-emission short-haul flights and advanced air mobility services, with ongoing demonstrations in Europe and North America (Clean Sky Joint Undertaking, 2024). By analyzing advancements in these technologies, this study highlights their potential impact on aviation sustainability and the barriers that must be overcome for widespread adoption.
From a broader sustainability perspective, this study is significant because it integrates technological, economic, and policy dimensions. Aviation is a hard-to-abate sector with long investment cycles, meaning that short-term solutions like SAF must be complemented by long-term innovations in propulsion, aircraft design, and operational efficiency (IEA, 2025; Our World in Data, 2024). The study also considers how emerging infrastructure developments, such as hydrogen refueling networks and SAF blending facilities, will shape the pace and effectiveness of decarbonization efforts (Sharma & Arief, 2024).

The findings have practical significance for policymakers, airline operators, aircraft manufacturers, and fuel producers, offering insights into the most promising pathways for achieving meaningful emissions reductions in aviation. By identifying critical success factors and challenges, the study provides a roadmap for coordinated action among stakeholders. Furthermore, it contributes to the academic discourse on sustainable transport by addressing a key gap in existing literature: the need for comparative analysis of near-term and long-term decarbonization strategies for aviation. These insights will support global efforts to meet climate commitments under the Paris Agreement and align with the broader United Nations Sustainable Development Goals (SDGs) (Ambrosio et al., 2025; Zubi et al., 2024).

4. Objectives of Study:

- To study the current contribution of the aviation sector to global greenhouse gas emissions and identify the key drivers influencing its carbon footprint
- To evaluate the economic viability of SAF adoption by comparing production costs with conventional jet fuels and identifying policy measures that can bridge the price gap
- To examine the technological readiness of emerging green propulsion systems, including hydrogen-powered and electric aircraft, and their projected contribution to medium- and long-term decarbonization
- To explore infrastructure and supply chain challenges associated with SAF production, hydrogen refueling, and electric charging systems necessary for the aviation transition

- To identify the roles of policy frameworks, international collaboration, and industry coalitions in accelerating the deployment of alternative fuels and green technologies across regions

5. Review of Literature

The existing literature on Sustainable Aviation Fuels (SAFs) emphasizes their critical role in decarbonizing the aviation sector. Bonicontro Ambrosio et al. (2025) conducted a detailed bibliometric analysis of HEFA-SPK and ATJ production pathways, highlighting that SAF can reduce lifecycle greenhouse gas emissions by up to 80% while maintaining compatibility with current aircraft engines and airport infrastructure. Similarly, a comprehensive review published in Transport Policy (2025) of 243 SAF-focused studies demonstrated increasing attention on feedstock diversification, technological efficiency, and policy-driven adoption strategies. The UK's GRIM-SAF initiative further validated environmental performance benefits, finding that 100% SAF blends reduce particulate and soot emissions compared to Jet A-1, thus addressing both CO_2 and air quality concerns (Martinez et al., 2025). These studies collectively suggest that SAF is the most viable near-term option for decarbonization.

Despite the promising attributes, scalability challenges persist. A report by the Institute for Policy Studies (2024) warned that tripling SAF production by 2030, as targeted by multiple governments, could divert resources from other climate mitigation measures and create unintended land-use and food security trade-offs. Similarly, a Boston Consulting Group (BCG) analysis indicated that SAF output is likely to fall 30–45% short of 2030 mandates due to feedstock scarcity, limited production capacity, and production costs three to five times higher than conventional jet fuel (Reuters, 2025). While oil majors such as BP and Shell are investing in over 40 SAF projects globally, the sector's cost competitiveness remains uncertain (Reuters, 2024). These findings underline the urgent need for robust regulatory frameworks and economic incentives to bridge the cost gap and secure long-term SAF supply chains.

Parallel research on hydrogen propulsion technologies demonstrates strong potential for medium- to long-term emission reductions. Sharma and Arief (2024) modeled hydrogen fuel cell systems for light aircraft and found that they could reduce emissions by up to 74.7%, although challenges remain in fuel storage, cryogenic handling, and certification. Broader reviews published in Energy & Fuels (Fawcett et al., 2025) and the AIAA Journal (Lopez et al., 2025) identified that hybrid-electric and hydrogen aircraft require significant advances in energy density, thermal management, and materials engineering. Demonstration projects such as ZeroAvia's HyFlyer and Project Fresson in the UK show technical feasibility for regional aviation but are far from commercial readiness for larger aircraft (ZeroAvia, 2025). These studies reinforce that hydrogen is a promising solution but one that will require transformative infrastructure investments and continued research.

Engineering studies have also explored the material and aerodynamic challenges of hydrogen adoption. Long et al. (2025) developed a multiscale model revealing that hydrogen embrittlement in stainless steel and nickel alloys can compromise fuel tank durability, necessitating the development of hydrogen-resistant materials. Similarly, Zhang et al. (2023) used computational fluid dynamics to analyze aerodynamic penalties of hydrogen tank integration in small aircraft, finding drag increases of up to 67% depending on storage configurations. These technical barriers add complexity to aircraft redesign efforts and highlight why the European Clean Aviation Programme has intensified its focus on lightweight composite materials and advanced aerodynamics (Clean Sky Joint Undertaking, 2024).

Industry and policy perspectives highlight the urgency and scale of the aviation decarbonization challenge. Reuters (2025) reported that hydrogen-powered circumnavigation efforts led by Bertrand Piccard aim to accelerate innovation but also underscore symbolic ambition rather than near-term feasibility. The Financial Times (2025) found that the European Union has downgraded its expectations for hydrogen aviation, projecting that it will account for just 6% of total sectoral emissions reductions by 2050, down from earlier estimates of 20%, primarily due to escalating costs exceeding €1.3 trillion. These insights illustrate that while SAF provides the best immediate pathway, hydrogen and electric propulsion technologies must mature in parallel to achieve long-term sustainability. Collectively, the literature indicates that decarbonization of aviation requires a multi-pronged approach, integrating SAF adoption, investment in breakthrough technologies, and global policy collaboration to overcome economic, infrastructural, and regulatory barriers.

6. Discussion and Analysis:

The adoption of Sustainable Aviation Fuels (SAF) is largely being driven by regional mandates and policy interventions; however, challenges surrounding production and cost persist. For instance, the European Union's ReFuelEU Aviation regulation requires a minimum 6% SAF blend by 2030, and the United Kingdom has set a 10% target for the same period. Despite these mandates, IATA (2025) forecasts that SAF supply will meet only 0.7% of global aviation fuel demand in 2025, leaving a significant shortfall. Industry leaders argue that import-dependent approaches to meeting these targets—such as sourcing SAF from Asia—could increase lifecycle emissions due to logistics-related carbon impacts (Reuters, 2025a). Airlines including Ryanair and Lufthansa have called for stronger domestic production capabilities, echoing concerns from Shell's CEO that policy ambition alone is insufficient without infrastructure investment and financial support to make SAF commercially competitive (The Times, 2025).

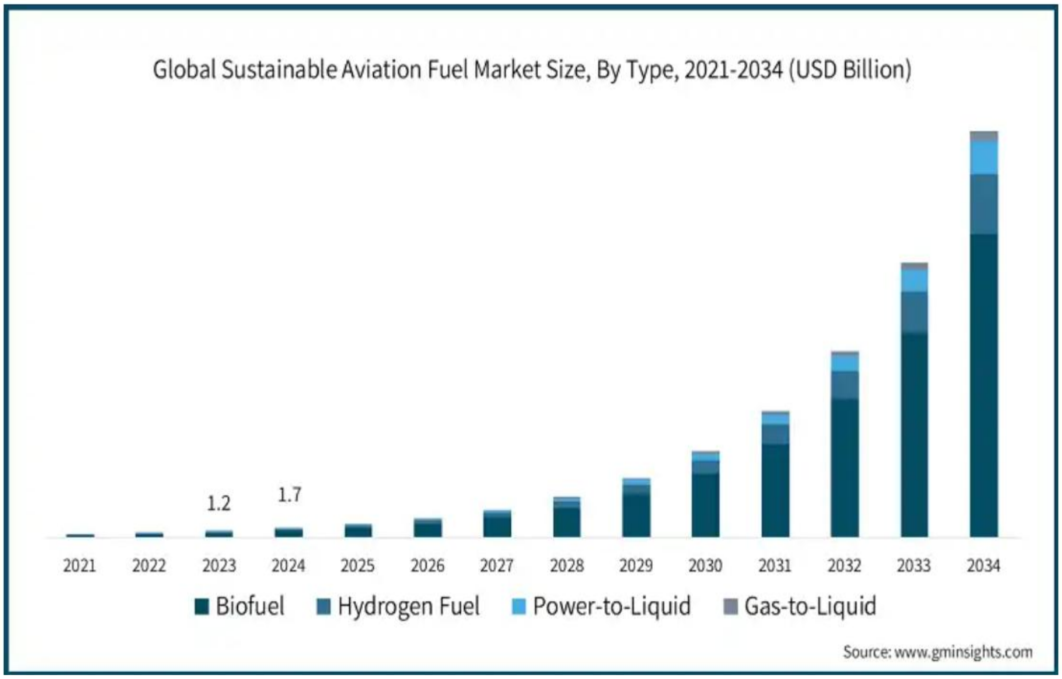
Economic constraints continue to be one of the most significant barriers to scaling SAF adoption. The World Economic Forum (2025) reports that SAF production costs remain three to five times higher than conventional jet fuel, creating a persistent price gap. Even with more than 40 SAF projects announced by oil majors such as BP and Shell, global capacity is unlikely to meet 2030 demand targets without targeted financial incentives (Reuters, 2024). Additionally, a Transport & Environment (2025a) study highlighted that technological improvements in aircraft design could reduce overall emissions by up to 13% by 2050, yet delays in innovation may negate much of the impact from cleaner fuels. These findings suggest that fuel-based strategies must be complemented by advancements in aircraft efficiency and stronger economic mechanisms, such as carbon pricing and low-interest green finance, to accelerate the transition.

Technological innovation, particularly in hydrogen-electric propulsion, shows promise for medium- to long-term decarbonization. ZeroAvia's (2024) development of the ZA600 and ZA2000 hydrogen-electric engines for regional aircraft is a step forward, but their application is currently limited to smaller planes. Hybrid-electric fuel cell systems must overcome significant hurdles in energy density, thermal management, and certification before being viable for commercial jets (Nature Energy, 2025; ScienceDirect, 2024). Furthermore, infrastructure needs such as cryogenic hydrogen storage and refueling networks remain largely undeveloped, posing additional challenges. These limitations underscore the importance of investing in foundational research and public-private partnerships to bring hydrogen-powered aviation into mainstream service in the coming decades.

Airframe and aerodynamic innovations also play a critical role in reducing emissions. Blended wing body (BWB) designs have been shown to decrease drag by up to 50% in optimal configurations, enabling significant fuel savings when paired with cleaner fuels or propulsion systems (Wikipedia, 2025). However, research by Transport & Environment (2025b) warns that delays in adopting such advanced aircraft designs risk undermining the sector's decarbonization potential. The integration of lightweight composite materials and advanced aerodynamics is essential for reducing energy demand, particularly for hydrogen-powered aircraft that face storage and volume penalties (ScienceDirect, 2024). Aligning these innovations with SAF deployment and hydrogen-electric propulsion could create synergies that make long-term climate targets achievable.

A dual-track strategy is necessary for aviation to meet its 2050 net-zero emissions target. SAF offers an immediate pathway to emissions reductions using existing fleets, while hydrogen-electric propulsion and aircraft design innovations represent transformational solutions for the future. However, this transition faces systemic challenges: high SAF costs, limited feedstock availability, lagging infrastructure development, and delayed aircraft innovation. Addressing these barriers will require coordinated international policies, strategic public and private investment, and collaborative industry action (World Economic Forum, 2025). Only by combining short-term scalability with long-term innovation can the aviation sector effectively reduce its carbon footprint while continuing to meet growing global travel demand.

Figure 1: Global Sustainable Aviation Market Size



The above figure illustrates the projected growth of the global Sustainable Aviation Fuel (SAF) market by type from 2021 to 2034, measured in USD billions. The data reveals a modest market presence between 2021 and 2025, with biofuel dominating the sector. A noticeable acceleration begins around 2026, driven mainly by increased adoption of biofuel, while hydrogen fuel, power-to-liquid, and gas-to-liquid technologies gradually contribute larger shares. By 2030, the market experiences substantial expansion, with multi-fuel diversification becoming evident. The growth trajectory steepens sharply after 2031, culminating in 2034 with the largest projected market size, where biofuel remains the leading segment but with significant contributions from hydrogen-based and synthetic liquid fuels. This trend highlights the aviation sector's shift toward diversified, low-carbon fuel alternatives to meet sustainability targets and reduce greenhouse gas emissions.

7. Findings of Study:

- The study reveals that Sustainable Aviation Fuel (SAF) remains the most feasible near-term solution for reducing aviation emissions. SAF, particularly HEFA-SPK, ATJ, and SAF from waste-derived feedstocks, has been consistently shown to reduce lifecycle CO_2 by 60–98%, depending on feedstock and technology route (Bonicontro Ambrosio et al., 2025; Martinez et al., 2025). Despite the strong emission reduction potential, global SAF production reached only around 0.7% of total jet fuel demand by mid-2025, limited by production capacity, high cost (3–5× conventional jet fuel), and feedstock constraints (IEA, 2025; World Economic Forum, 2025). These findings underscore the continued need for policy mechanisms—such as blending mandates, low-carbon fuel standards, and fiscal incentives—to bridge the gap between potential and scale.
- Green propulsion technologies, including hydrogen-electric and electric aircraft, exhibit high promise for medium- to long-term decarbonization. Demonstration programs like

ZeroAvia's ZA600 for regional aircraft—and forthcoming ZA2000—demonstrate the technical viability of hydrogen fuel cell propulsion, potentially reducing emissions by up to 75% (Sharma & Arief, 2024; ZeroAvia, 2024). However, the practical rollout of these systems remains constrained by limited energy density, substantial weight penalties, and storage challenges, particularly in cryogenic refrigeration and materials engineering (Nature Energy, 2025; Long et al., 2025). These limitations highlighted that hydrogen-electric aviation will likely remain niche and constrained to regional operations through the 2030s.

- This analysis also highlights the critical role of aircraft design and aerodynamics in maximizing carbon gains across both fuel- and propulsion-based strategies. Innovations such as blended wing body (BWB) configurations and lightweight composites can reduce drag and improve efficiency by 20–50%, creating synergistic effects when paired with SAF or future propulsion systems (Wikipedia, 2025; Transport & Environment, 2025b). Nonetheless, deployment of these designs is delayed by slow R&D cycles, certification complexity, and manufacturing adaptation efforts. Without timely progress, aerodynamic gains risk being overshadowed by fuel supply bottlenecks and technological readiness.
- Another key finding is the emergence of policy and infrastructure barriers that impede widespread adoption. While mandates like ReFuelEU and SAF targets in the UK and California provide demand-side signals, discrepancies between policy ambition and actual supply availability remain unaddressed (Reuters, 2025a; AP News, 2024).
- The lack of infrastructure for hydrogen refueling and SAF blending facilities presents a significant gap, especially in regions with limited domestic production capacity. Private-sector investment alone may be insufficient—coordinated public-private initiatives, international collaboration, and strategic finance instruments (e.g., green bonds, SAF credits) are needed to fill these infrastructure voids (World Economic Forum, 2025).
- The study demonstrates that a dual-track strategy—using SAF to achieve immediate emissions reductions while investing in future hydrogen-electric propulsion and design innovation—is essential for meeting aviation's net-zero targets by 2050. However, this approach hinges on robust alignment between policy frameworks, technological maturity, supply chain coordination, and economic incentives.
- Stakeholder coordination across airlines, fuel producers, manufacturers, and governments emerges as a critical factor. Collectively, the evidence suggests that without these integrative efforts, aviation decarbonization ambitions risk falling short due to gaps between technological potential and operational reality.

8. Conclusion

The study underscores that achieving net-zero carbon emissions in aviation by 2050 requires a comprehensive and multi-dimensional approach. Immediate emissions reductions can be achieved through Sustainable Aviation Fuels (SAF), which offer up to 98% lifecycle emission savings, depending on the production pathway and feedstock (Bonicontro Ambrosio et al., 2025; Martinez et al., 2025). SAF remains the most feasible near-term solution as it is compatible with existing fleets and airport fueling infrastructure, allowing rapid integration. However, global production still accounts for less than 1% of jet fuel demand, highlighting the pressing need for massive scale-up efforts (IEA, 2025; World Economic Forum, 2025). Without addressing the

supply and cost constraints through policy and investment, aviation emissions will continue to rise despite technological advancements.
The findings also emphasize that hydrogen-electric propulsion systems and electric aircraft are essential components of a long-term decarbonization strategy. Demonstration projects such as ZeroAvia's ZA600 and ZA2000 hydrogen-electric engines show the technical viability of these solutions, which could reduce emissions by 70–75% for regional aviation (Sharma & Arief, 2024; ZeroAvia, 2024). Yet, significant hurdles persist, including energy density limitations, cryogenic storage challenges, and infrastructure requirements for hydrogen refueling (Nature Energy, 2025; Long et al., 2025). These limitations indicate that hydrogen and electric propulsion will likely remain confined to short-haul and regional flights for the foreseeable future, reinforcing the need for parallel investment in SAF to decarbonize long-haul operations.

Another key insight is the importance of aircraft design innovation and operational efficiency. Advancements such as blended wing body (BWB) airframes and lightweight composite materials can reduce drag by up to 50%, enabling more efficient fuel and energy use (Wikipedia, 2025; Transport & Environment, 2025). However, the slow pace of aircraft certification and redesign may delay the realization of these benefits. Combining aerodynamic improvements with SAF and hydrogen propulsion could create synergies that significantly accelerate progress toward decarbonization targets. Airlines and manufacturers must prioritize R&D and collaborate to shorten innovation timelines while maintaining safety and certification standards.

Policy alignment and infrastructure investment emerge as the most critical enablers of aviation's transition. SAF blending mandates such as ReFuelEU and financial incentives like tax credits and low-carbon fuel standards provide necessary demand signals, but these must be paired with robust support for scaling production and establishing hydrogen and SAF infrastructure (AP News, 2024; Reuters, 2025a). International cooperation is also vital, as the global nature of aviation requires harmonized standards and market-based measures to avoid fragmentation. Public-private partnerships and innovative financing tools, including green bonds and SAF credits, can help bridge funding gaps and de-risk large-scale investments (World Economic Forum, 2025).

This study highlights the need for a dual-track strategy: leveraging SAF for immediate impact while simultaneously investing in hydrogen-electric propulsion, aircraft design innovation, and supporting infrastructure. Achieving meaningful reductions will require coordinated action across policymakers, airlines, manufacturers, and fuel producers to close the gap between ambition and feasibility. Without such alignment, aviation decarbonization risks falling short, undermining global climate targets. Conversely, by integrating short-term scalability with long-term technological transformation, the aviation industry can transition to a sustainable future that balances environmental responsibility with continued global connectivity (IEA, 2025; Nature Energy, 2025).

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