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A Brief Review of Models and Predictions for Achieving Carbon Neutrality in Civil Aviation [#]

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ABSTRACT

To achieve the 1.5 °C climate goal, global aviation must reach net-zero CO_2 emissions around 2050. Yet, aviation is widely regarded as a "hard-to-abate" sector due to its strong reliance on high-energy-density liquid fuels. This paper briefly reviews and compares decarbonization models and pathways published by major organizations such as ICAO, IATA, ATAG and ICCT. Key findings include: (1) Sustainable aviation fuel is viewed across all major scenarios as the primary emissions reduction lever during 2030–2050. (2) Revolutionary technologies such as hydrogen/electric propulsion exhibit the highest level of uncertainty. (3) Operational improvements are unable to fully offset demand growth. (4) Sector-internal measures alone cannot achieve absolute zero emissions by 2050; external market-based measures or carbon dioxide removal will be necessary. The study further notes that current models are evolving toward integrated techno-economic-policy-climate assessments, AI-enhanced interpretable projections, and improved accounting of non-CO_2 effects and socio-economic impacts.

Keywords: civil aviation, decarbonization pathway, net-zero CO_2 emissions, integrated model

NOMENCLATURE

Abbreviations	
AI	Artificial Intelligence
ATAG	Air Transport Action Group
CDR	Carbon Dioxide Removal
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
LTAG	Long-Term Aspirational Goal
MBM	Market-Based Measure
SAF	Sustainable Aviation Fuel

1. INTRODUCTION

Achieving net-zero carbon dioxide (CO_2) emissions by the mid-century—an essential condition for limiting anthropogenic warming to 1.5 °C above pre-industrial levels—requires transformative mitigation across all economic sectors. However, civil aviation poses distinctive challenges: prior to the COVID-19 pandemic, the industry accounted for over 2% of global energy-related CO_2 emissions, with a growth trajectory that outpaced many other transport sectors. As a "hard-to-abate" sector, aviation relies on energy-dense liquid fuels for which there are few readily available, scalable, and low-carbon alternatives.

In response, the International Civil Aviation Organization (ICAO) established a Long-Term Aspirational Goal (LTAG) of net-zero carbon emissions by 2050[1]. This policy inflection has catalyzed a proliferation of sectoral decarbonization pathways developed by industry coalitions—including the Air Transport Action Group (ATAG)[2], International Air Transport Association (IATA)[3], and International Council on Clean Transportation (ICCT)[4]—and independent research institutions[5]. While these modeling frameworks provide critical insights into technological feasibility and mitigation costs, they diverge substantively in system boundaries, scenario assumptions, and projected contributions of specific levers.

This paper provides a brief review and synthesis of these models and their corresponding predictions. Its primary objective is to critically assess the state-of-the-art in modeling aviation’s pathway to carbon neutrality

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by: (1) outlining the primary modeling frameworks that have been employed to analyze decarbonization pathways; (2) comparing the key assumptions and predicted contributions of each major mitigation lever across different decarbonization pathways; and (3) identifying deficiencies in current modeling research, such as inadequate consideration of non-CO_2 impacts and uncertain factors, and putting forward targeted recommendations for future research advancements.

2. MODELING FRAMEWORK IN AVIATION DECARBONIZATION

Figure 1 outlines a systemic framework for analyzing aviation decarbonization. It illustrates the interdependencies among aircraft, airport, and air traffic management subsystems driven by passenger and freight demand. Environmental impacts (CO_2 and non-CO_2 emissions) and economic costs are generated through these subsystems. Key features include: (1) dual-layer feedback structures—inner loops (operational efficiency-cost-demand elasticity) and outer loops (policy-learning-carbon pricing); (2) four mitigation pillars—sustainable aviation fuel (SAF), technology development, operational improvements, and out-of-sector measures; and (3) cross-modal competition effects. The framework supports integrated techno-economic assessments of low-carbon transition strategies.

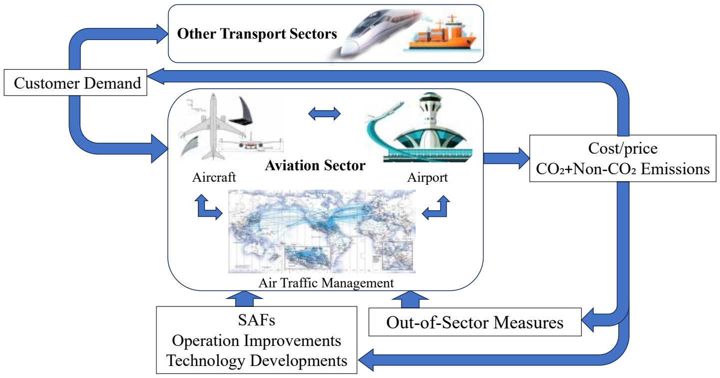

Fig. 1 Systemic analytical framework for aviation decarbonization

2.1 Foundational Models for Emission Accounting

Rigorous decarbonization pathways depend upon accurate baseline emission inventories and their attribution to specific driving forces. Current practice employs two complementary methodological paradigms: (1) Decomposition analysis. At the macro level, index decomposition analysis is widely applied to attribute historical emission changes to activity levels (passenger-kilometers), fleet structure, energy intensity, and carbon factor effects. (2) Process-level inventories. Micro-level approaches employ emission factors derived from fuel consumption data. In addition, dedicated models have been developed for particular flight phases — such as the landing-and-take-off cycle — to assess local air-quality impacts and the mitigation potential of airports.

2.2 Aviation Activity Coverage and Emissions Scope

International organizations typically target the global market, such as ICAO, whereas government agencies focus on regional or domestic contexts, such as EU+[6], UK[3], USA[7]. Commercial passenger traffic is the most fundamental starting point for mapping net-zero aviation pathways; to enrich such analyses, freight markets receive greater attention.

Carbon dioxide emissions from commercial passenger flights are the most fundamental issue in the transition toward green aviation. Some studies also account for other market segments, as well as full life-cycle CO_2 and non-CO_2 emission impacts.

2.3 Integrated Scenario Modeling

Long-term decarbonization assessments rely predominantly on integrated scenario modeling to explore uncertainties in technological availability and socio-economic development. These models generally fall into two categories. Top-down approaches, such as computable general equilibrium models, adopt a macroeconomic perspective but often lack detailed representation of energy technologies. In contrast, bottom-up models are engineering-based and provide detailed descriptions of energy conversion technologies and processes, allowing for analysis of how technological changes affect the broader energy-economy system. In the aviation sector, most existing studies adopt a top-down approach to forecast CO_2 emissions and intensity, as well as to assess the economic implications of carbon neutrality scenarios.

3. ANALYSIS OF KEY DECARBONIZATION LEVERS AND PREDICTIONS

The pathways to net-zero aviation are built upon the combined impact of several mitigation levers. The various models and pathways reviewed offer a range of predictions about the potential contribution of each lever, reflecting different assumptions about technological progress, economic feasibility, and policy ambition. Figure 2 summarizes the emissions reduction contributions attributed to each lever for each pathway in 2050.

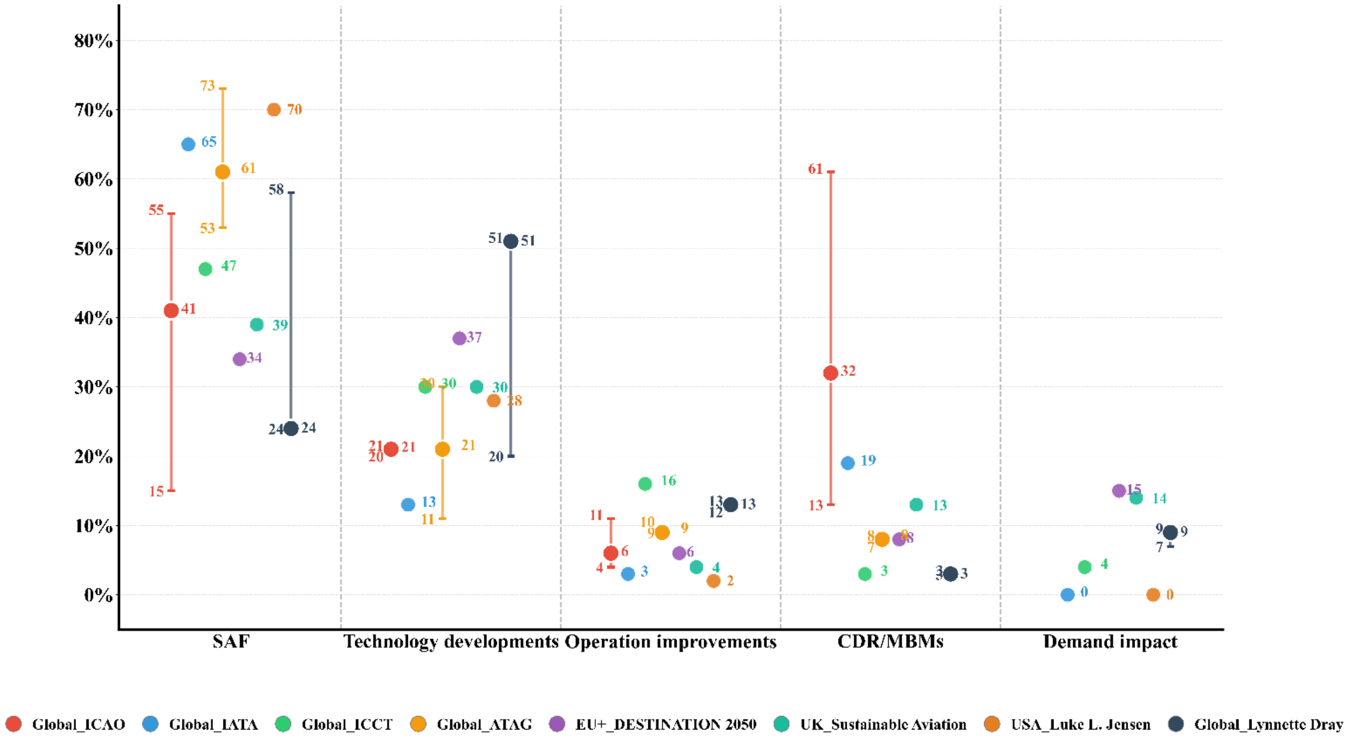

Fig. 2 Emissions reduction potential by mitigation levers for each pathway in 2050

3.1 SAF

Across all ambitious net-zero scenarios, drop-in SAF—synthetic hydrocarbons compatible with existing airframes and infrastructure—constitutes the largest single mitigation contribution. Median projections indicate SAF will deliver 53% of the required emissions reductions by 2050, compensating for residual fossil-fuel use in long-haul aviation where alternative propulsion remains non-viable.

However, the scale-up of SAF faces monumental challenges: (1) Cost. At two to six times the price of conventional jet fuel, SAF imposes an immediate and heavy financial burden on airlines; even under optimistic learning-curve assumptions, a sizable price gap is expected to persist for years, exerting upward pressure on fares. (2) Feedstock. Sustainable bio-feedstocks—waste oils, residues, energy crops—are scarce and highly contested by road transport and chemicals, raising red flags for land-use, food security and sustainability concerns. Power-to-liquid pathways face an equally stark bottleneck: vast quantities of renewable electricity and captured CO_2.

3.2 Aircraft Technology Developments

The long-term vision for aviation includes a shift to zero-emission propulsion technologies, primarily hydrogen combustion or fuel cells and battery-electric systems. However, their application is constrained by the low energy density of batteries and the volumetric challenges of storing liquid hydrogen. Due to the weight of batteries, all-electric aircraft are only considered viable for very short-range flights (e.g., less than 500 km) and small commuter aircraft in the 2050 timeframe. Their overall contribution to emissions reduction in global models is therefore predicted to be minimal. Hydrogen offers a more promising pathway for short- to medium-haul flights[8]. However, it would require entirely new aircraft designs and a complete overhaul of airport fueling infrastructure. Taking into account aviation airworthiness and safety requirements, most pathways conclude that electric and hydrogen propulsion cannot play a major role in the sector's green transition before 2050 and therefore do not subject them to explicit quantitative assessment[9]. In contrast, pathways with a strong European focus, like DESTINATION 2050[6], predict a much larger role for hydrogen, contributing over 37% of emissions reductions. This wide variance underscores that the future of hydrogen in aviation is one of the biggest uncertainties in the path to net-zero.

3.3 Operation Improvements

Continuous operation improvement in the energy efficiency of aircraft and air traffic operations is a foundational element of every decarbonization pathway. Historically, the energy intensity of aviation has improved by approximately 1-2% per year, driven by the introduction of more efficient aircraft and operational enhancements[10].Future gains are expected from advanced aircraft designs, including more efficient engines, lightweight composite materials, and improved aerodynamics. Most pathways project an annual fleet-wide efficiency improvement of around 1.1–1.5% from technology alone[9]. Air traffic management and ground operations contribute marginal gains via trajectory optimization and continuous descent approaches. Collectively, operational measures account for 2–16% of 2050 emissions reductions across scenarios—a "necessary but not sufficient" condition for net-zero.

3.4 Out-of-Sector Measures

A critical and sobering conclusion from most comprehensive models is that in-sector measures alone are unlikely to achieve absolute zero emissions by 2050. Consequently, almost all global pathways suggest that the aviation sector will need to rely on out-of-sector measures to bridge this final gap. These measures fall into two main categories: (1) Market-based measures (MBMs). These include carbon offsetting schemes like ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and emissions trading systems. Airlines can purchase carbon credits from projects that reduce emissions in other sectors to compensate for their own. (2) Carbon dioxide removal (CDR). To achieve true net-zero, particularly when accounting for the warming effects of non-CO_2 emissions, it may be necessary to actively remove CO_2 from the atmosphere through technologies like direct air capture or nature-based solutions[11].

3.5 Demand Impact

The most direct, albeit contentious, lever for reducing emissions is managing the growth in demand for air travel. Business-as-usual projections, based on historical correlations with economic growth, often forecast a tripling or quadrupling of demand by 2050 compared to pre-pandemic levels[10]. However, a growing number of analyses incorporate demand management as a key mitigation strategy. Ambitious demand reduction scenarios propose that behavioral changes, modal shifts to high-speed rail for short-haul routes, and increased use of virtual collaboration should significantly curb demand growth. Most industry-led pathways are more conservative, either assuming continued strong growth or modeling only minor demand impacts resulting from increased ticket prices. For example, the DESTINATION 2050[6] report for European aviation attributes approximately 15% of emissions reductions to demand impacts.

4. DISCUSSION

4.1 Synthesis of Findings

The modeling work on aviation decarbonization demonstrates that while pathways to net-zero emissions by 2050 are technologically plausible, they are contingent on an unprecedented and rapid transformation of the entire aviation ecosystem. The convergence of findings across multiple, independent pathways lends credibility to several key conclusions, while the divergences highlight areas of profound uncertainty that demand strategic attention.

A primary point of consensus is the elevation of Sustainable Aviation Fuels from a niche alternative to the cornerstone of the industry's climate strategy. This finding has profound policy implications. It signals that the most urgent priority for governments and industry is to create the conditions necessary for a global SAF market to emerge. This includes implementing policies that bridge the significant price gap with conventional fuel, such as production incentives, mandates, and carbon pricing [7]. Furthermore, the models' reliance on vast quantities of SAF underscores the critical need for robust sustainability criteria to govern feedstock sourcing and production, ensuring that the solution to aviation's climate problems does not create new environmental or social crises.

The consistent finding that residual emissions are likely to remain in 2050, requiring out-of-sector measures, is another crucial insight. It forces a pragmatic conversation about the definition of "net-zero" for a hard-to-abate sector. It implies that the aviation industry's success will be linked to the development and integrity of global carbon markets and CDR technologies. This dependency creates both a risk and an opportunity. The risk is that an over-reliance on offsets could dilute the incentive for in-sector abatement. The opportunity is for the aviation sector to become a key source of demand that helps scale and drive down the cost of high-quality CDR, benefiting the global climate effort.

In contrast, the wide variance in predictions for hydrogen and electric aircraft reveals a critical juncture in long-term strategy. The uncertainty modeled by different organizations reflects a genuine technological and economic crossroads. While these technologies offer the promise of zero in-flight emissions, their development is at a much earlier stage and requires revolutionary changes to aircraft and infrastructure. This suggests a two-pronged policy approach is necessary: an immediate and aggressive focus on scaling up "drop-in" SAF for the existing and near-term fleet, coupled with sustained, long-term R&D investment to mature hydrogen and electric technologies as the potential next-generation solution for short- and medium-haul travel.

4.2 Future Research Directions of Modeling

All models are simplifications of reality and have inherent limitations. Firstly, most frameworks struggle to fully capture the complexities of non-CO_2 climate impacts, which constitute a significant portion of aviation's total warming effect. As scientific understanding of these effects improves, models will need to incorporate them more dynamically. Secondly, the socio-political feasibility of certain assumptions—such as sustained high levels of investment, global policy coordination, or significant behavioral shifts in travel patterns—is often simplified. The pathways are technically modeled, but their real-world implementation will be a complex negotiation between economic interests, political will, and public acceptance. Thirdly, long-term forecasts are subject to high uncertainty, particularly regarding technological breakthroughs and socio-economic shifts. Although several machine-learning models have been applied to aviation-decarbonization studies[12], their "black-box" nature obscures the underlying logic; ensuring that model-driven decisions remain transparent and trustworthy is therefore imperative.

To address these challenges, future research should focus on several key areas: (1) Non-CO_2 effects. The current focus on "carbon neutrality" primarily addresses CO_2. However, aviation also has significant non-CO_2 climate impacts from sources like contrails and nitrogen oxides. Future research and modeling must incorporate these effects to develop a truly climate-neutral aviation system. (2) Integrated modeling. There is a need for more holistic models that integrate technological, economic, operational, and policy dimensions. These models should be able to capture the complex feedback loops between different parts of the aviation system and its interaction with the broader economy and energy sector. (3) Socio-economic analysis. The transition will have profound socio-economic consequences. More research is needed to understand the impacts on employment, supply chains, regional development, and the accessibility and affordability of air travel for the global population. (4) Advanced artificial intelligence (AI) applications. Research should continue to push the boundaries of AI and machine-learning in aviation, focusing on improving the accuracy, robustness, and interpretability of predictive models. This includes developing digital twins of aircraft, airports, and air traffic networks for comprehensive simulation and optimization.

5. CONCLUSION

This paper reviewed typical models and predictions for achieving carbon neutrality in civil aviation. The synthesis of these studies yields several clear and actionable conclusions for stakeholders across the aviation value chain.

First and foremost, SAF is the linchpin of every credible mid-term decarbonization pathway. The consensus across all major pathways is that SAF must shift from a marginal fuel source to the dominant form of aviation energy within three decades, accounting for the majority of emissions reductions. The most critical and immediate task is to catalyze a global SAF industry through robust policy support, technological innovation, and massive capital investment.

Second, the role of novel propulsion systems like hydrogen and battery-electric aircraft remains a significant uncertainty. While they hold the long-term promise of eliminating in-flight emissions, their impact by 2050 is highly contested across different models, with their application likely limited to shorter-range markets. Simultaneously, sustained R&D is required to mature these revolutionary technologies.

Third, while efficiency gains from improved operations are essential, they are insufficient to counteract projected demand growth. They must be pursued relentlessly to reduce the sheer volume of alternative fuel required, but they are not a substitute for the fundamental energy transition.

Finally, all climate impacts from in-sector measures alone are unlikely by 2050. A reliance on high-quality carbon offsets and removals to address residual emissions appears unavoidable. This reality underscores the need for the aviation sector to engage constructively in the development of robust and transparent carbon markets and to support the scaling of credible CDR technologies.

Looking forward, the future modeling for aviation carbon neutrality will prioritize integrated approaches, combining technological, economic, operational, and policy dimensions to capture systemic feedback and economy-wide interactions. Greater emphasis will be placed on non-CO_2 effects which significantly contribute to warming. Socio-economic analyses will be expanded to assess impacts on employment, supply chains, regional development, and air travel accessibility. Emerging technologies like direct air capture and advanced carbon removal will be critically evaluated for their role in achieving net-zero. Models will dynamically simulate policy and market mechanisms to compare emissions reduction pathways and economic costs. Multi-scenario analyses will explore diverse technological, policy, and behavioral options to map emissions trajectories. The integration of big data and AI will improve model accuracy, transparency, and predictive capability. Together, these advances will support a structured transition to a carbon-neutral aviation sector.

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