# Sustainable Approach for Future Aviation

## Sustainable Aviation Fuel Partnerships and Fleet Modernization


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Anjalee Ranpati Dewage

## Abstract

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Abstract

The objective of this thesis is to evaluate the contribution of Sustainable Aviation Fuel (SAF) partnerships and fleet modernization towards a sustainable future in the aviation industry. The purpose is to explore the effectiveness of these strategies and further advancements needed to ensure that long-term sustainability goals are achieved. The research is carried out in an unbiased manner depending exclusively on secondary data resources.

The thesis follows a qualitative approach concentrating on secondary data gathered from academic papers, annual sustainability reports from airlines, official organizational websites and international regulation documentaries. This thesis is centred around implementation of SAF and fleet modernization and relevant legislative and strategic operations. To strengthen the collected data, this thesis assesses the current strategic practices implemented by selected airlines.

The findings indicate that SAF implementation is highly encouraged around the world yet challenged by high production costs, limited infrastructure and restricted logistics issues, whilst fleet modernization is highly fuel-efficient, yet it needs huge investments. The research highlights the importance of partnerships, innovations and uniform global policies combining together to achieve long-term sustainable goals of the aviation industry.



Keywords

Sustainability, Aviation, SAF Partnerships, Fleet Modernization

**List of Abbreviations**

| | |
|---|---|
| AI | Artificial Intelligence |
| CORSIA | Carbon Offsetting and Reduction Scheme for International Aviation |
| EEA | European Economic Area |
| ESG | Environmental, Social and Governance |
| EU ETS | Europe Union Emissions Trading System |
| GCD | Green Claim Directive |
| IATA | International Air transport Association |
| ICAO | International Civil Aviation Organization |
| SAF | Sustainable Aviation Fuel |
| SDG | Sustainable Development Goals |

Contents

# 1 Introduction

## 1.1 Research Background

The aviation industry is a crucial mode of global transportation connecting people and businesses worldwide. Air travel has grown immensely throughout the past decades and has driven a large-scale contribution to economic development and globalization. On the other hand, this expansion is raising concerns regarding environmental pollution since airplanes are significant contributors of carbon and greenhouse gas emissions. The growing awareness on environmental sustainability, climate change, and nature healing, is now pushing governments, regulatory bodies, industry stakeholders, and researchers to dive into more sustainable alternatives and practices instead of traditional aviation operations. Airlines are under pressure to adopt more environmentally friendly operations, such as implementing sustainable fuel options rather than traditional jet fuel and employing fleet modernization strategies to improve efficient performances (Fliteline 2023).

To achieve these milestones, airlines are focusing on implementation of sustainable fuel partnerships and refined fleet modernization to reduce the industry's contribution to greenhouse gas emissions. Innovation of sustainable aviation fuel (SAF) with a lower carbon footprint as an alternative for traditional jet fuel has been a revolutionary approach where SAF is produced using renewable resources such as plant oils, agricultural residues, and other biodegradable waste materials (IATA). SAF is a promising approach to minimize the aviation emissions even though it is in early stages of production with challenges regarding manufacturing costs, logistics limitations, regulatory restrictions and limited supply-service relationships.

Furthermore, advancements in efficient fleet modernization are critical in the aviation industry to achieve long-term sustainability. A progressive investment in next-generation aircraft with efficient fuel consumption, less emissions and enhanced aerodynamics is visible among airlines. Moreover, airlines are strategically improving the operations of existing fleets by optimizing flight routes, shorter taxi times, and using lightweight materials that improve fuel efficiency by minimizing fuel consumption. Likewise, implementation of artificial intelligence (AI) and predictive maintenance is used to improve fleet efficiency and enhance lifespans of aircraft leading to long-term sustainability (Lu 2024).

This thesis is aimed at investigating these important aspects, including the significance of sustainable fuel partnerships and fleet management in the aviation industry. By analysing industrial trends, challenges and opportunities, this research provides valuable insights for a sustainable approach for future aviation. The findings improve understanding of measures for further sustainable establishment while preserving operational efficiency and economic viability.

## 1.2 Thesis Objectives, Research Questions, and Limitations

**Objectives**

The primary objective of the research is analysing the role of SAF partnerships and fleet modernization in improving environmental sustainability within the aviation industry. This thesis initially leads to an analysis of existing literature on sustainability challenges and opportunities within the industry. Afterwards, the analysis is strengthened by examining practical applications of SAF integration, fleet modernization and passenger engagement initiatives of selected airlines. Finally, the thesis concludes with an intensive discussion on findings, and providing practical recommendations for airlines, regulatory parties and relevant stakeholders to assist broader adoption of sustainable practices.

**Research Questions**

The thesis is guided by one main research question and two sub questions to address a broader range of data and identify successful solutions and practical remedies.

Main research question:

- How do sustainable fuel partnerships and fleet modernization contribute to a sustainable approach in future aviation?

Sub questions:

- What are the key challenges and opportunities in implementing SAF into airline operations?
- How does fleet modernization enhance fuel efficiency and minimize greenhouse gas emissions in aviation?

With thorough research, the thesis provides an effective comprehension on current aviation opportunities and challenges and identifying sectors which need more developments to enhance aviation sustainability.

**Limitations**

The research provides a comprehensive overview of sustainable aviation practices, but there are some limitations. The focus here is commercial aviation, where private and military aviation are not considered due to their different operational strategies. Further, the thesis does not consider economic and social sustainability and focuses only on environmental sustainability, which is the ultimate objective of fuel efficiency.

Another limitation is the difficulty in obtaining confidential corporate data from large-scale companies such as airlines and fuel suppliers. Since aviation sustainability initiatives are in early stages, most of the corporations consider their sustainable information to be confidential, making it difficult to obtain primary data for the study. To counter address this, the study collects more information from publicly available responsible data sources and previous academic research and creates an in-depth assessment regarding sustainable aviation. Nevertheless, the research provides an insightful outcome that benefits the aviation sector to achieve more sustainability.

## 1.3 Theoretical Framework

Several theoretical frameworks are used in understanding sustainable practices. They are the Circular Economy framework and Diffusion of Innovation Theory model. These frameworks are not explained but their logics and terms are referred to in analysing data and deriving recommendations.

Circular Economy framework is used in the thesis regarding circular economy principles within airlines in terms of fuel efficiency, aircraft retiring and recycling, and waste management. This framework helps in understanding sustainable fleet management and end-of-life aircraft procedure in a resource-efficient aspect.

The innovation of SAF, fuel efficient aircrafts and mechanisms and the scale of acceptance into the aviation industry with respect to regulatory bodies, technological advancements and customer demands are explained by identifying the early adopters, late majority and innovators of sustainable practices. Further, this thesis discusses possible benefits for innovators and early adopters within the industry according to the Innovation of Diffusion theory model.

## 1.4 Research Methodology and Data Collection

The study incorporates qualitative research method. As the initiative, the existing theories and frameworks are used and to guide more into the empirical data and recommendations, a deductive approach is implemented (Bhandari 2023).

**Research Methodology**

The research incorporates qualitative data. The qualitative research entails examining industry data, emission statistics to figure out the current sustainable trends. Further, a literature review is available on existing theories and frameworks regarding sustainable practices. This approach enables a thorough understanding of the elements affecting SAF relationships and fleet modernization.

**Data Collection Methods**

Secondary data sources are used in this research. This data is based on existing reports, publicly available industry data, previous academic research and sustainability reports of several selected airlines. These selected airlines are either pioneers in sustainable aviation or they are implementing unique practices to achieve sustainable goals.

## 1.5 Thesis Structure

The thesis structure of this study is as follows.

The introduction of the thesis provides an overall understanding of the research purpose, its importance and the methodology and data collection methods employed, while the literature review section provides a current roadmap on the existing studies and current airline industry to examine the current and future sustainable aviation trends and practices. In chapter 4, current strategic examples regarding sustainable practices from airlines are discussed.

Discussion chapter is regarding the presentation of the research findings and recommendations by analysing collected secondary data. The conclusion highlights the significance of the thesis by providing the solutions to address research questions and summarize the content of the entire thesis.

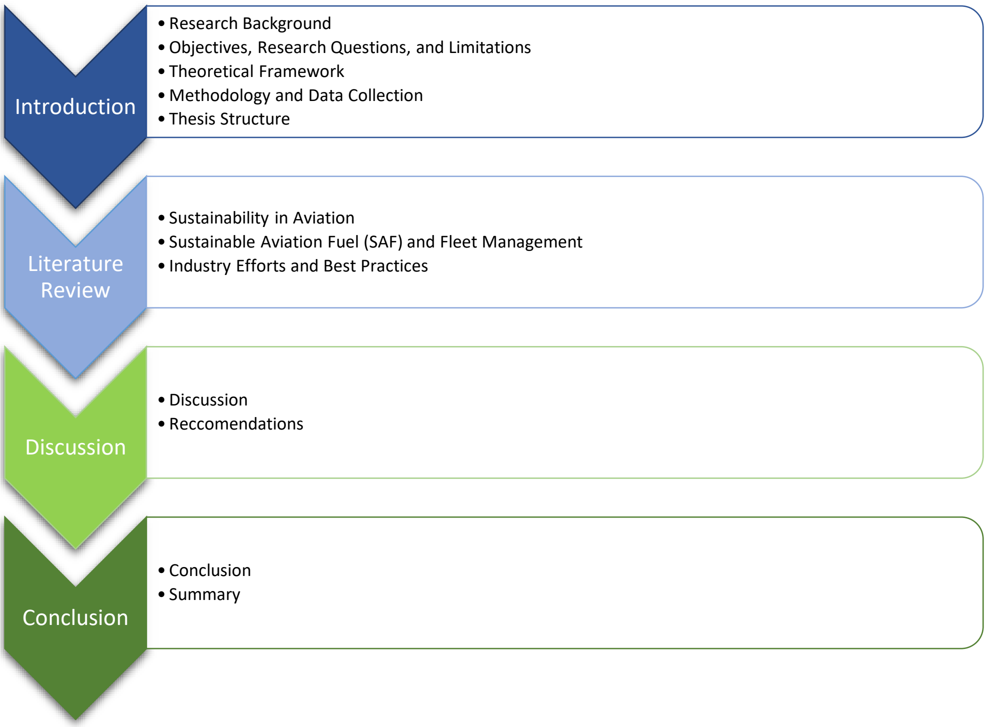


Figure 1. Thesis Structure

# 2 Sustainability in Aviation

## 2.1 Environmental Challenges and Regulatory Frameworks

The aviation industry is critical in networking the global economy yet its environmental impact particularly on greenhouse gas emission, noise pollution and excess resource consumption is gaining criticism from the public. According to the International Air Transport Association (IATA), aviation itself is responsible for approximately 3% of universal carbon dioxide emissions, and according to the European Commission that number is expected to grow three-fold as air transportation is rising and if no actions are taken (IATA; European Commission). Even though this number seemed to appear smaller compared to other industries, this impact is higher since they are released at high altitudes where their radiative forcing effect is amplified (Bolin Centre for Climate Research 2020, 3).

Another serious challenge in aviation is its high reliance on fossil fuels causing significant environmental issues. Airplanes are powered by jet fuel which is a derivative from purified crude oil. When burning, jet fuel releases not only carbon dioxide ($CO_2$) but also nitrogen oxides ($NO_x$), water vapour and other particles causing production of ozone and climatic changes. Moreover, contrails and cirrus clouds created from airplane exhausts cause serious impacts on atmospheric warming. (Overton 2022.) These critical impacts with long-term consequences highlight the importance of decarbonizing the aviation sector.

Aircraft $CO_2$ emission varies among aircraft types. Being responsible for 57% of emissions, wide-body aircrafts are the biggest contributor for carbon emission while 36% is from single-aisle aircrafts (Reed 2022). The remaining percentage is from regional jets, commuter aircrafts and general aviation as explained in Figure 2.

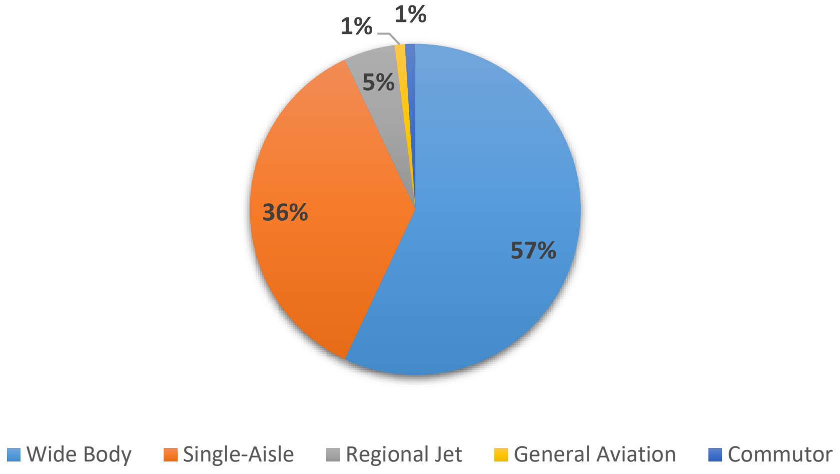


Figure 2. Aviation $CO_2$ emission by aircraft type (Reed 2022)

To address these challenges, regulatory frameworks have been developed by responsible international organizations are developing regulatory frameworks to safeguard the environment as well as the industry. The International Civil Aviation Organization (ICAO) took the initiative of launching the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). The aim of establishing CORSIA was to achieve carbon-neutral growth starting from 2020 by mandating the airlines to offset emissions exceeding 2020 levels. (Traficom 2024.) Even though CORSIA has shown some progress, there are critics saying that it is valid for a small percentage of emission and encourages airlines to purchase offsets rather than taking actions to reduce emissions at the source, raising the doubts about the long-term effectiveness and transparency. As per the Transport & Environment organization, which is Europe's leading clean transport and energy organization, CORSIA is the "the worst option for the climate". (Satair 2023.)

When the regional levels are considered, the Europe Union Emissions Trading System (EU ETS) is an important directive in managing aviation emissions. The strategy used by EU ETS is called cap-and-trade strategy that promotes emission reductions by assigning a cost to carbon. However, this is only applicable for flights within the European Economic Area (EEA) and flights departing to Switzerland and the United Kingdom, restricting its global reach (European Commission). This regulatory framework highlights the importance of the need for a more unified and aspirational global policy strategy. Unless a carbon leakage or market distortions occur as the emissions limits between regions vary, suppressing the goal of sustainable equality globally. (Kuusi & Wang 2022, 25.)

Another growing concern is the noise pollution, mostly around commercial airports. According to the ICAO's Annex 16 on environmental protection, responsible regulatory bodies have set noise standards, addressing aircraft noise certification requirements (ICAO). Despite modern aircrafts being quieter, rising air traffic volumes affect noise pollution as a major concern around airports. Further, regular exposure to noise for a long-term impact negatively on human health and according to the report by the European Parliament, these observations are common among the residents living around the urban airports (Cremaschi & Elliff & Huck 2021, 10).

To sum up, even though regulatory bodies are making progress towards environmental sustainability, more viable and long-term strategies such as establishing policies to encourage innovation, investment in greener technology and international collaborations are essential for the aviation industry.

## 2.2 Role of Sustainable Development Goals (SDGs)

The United Nations SDGs establish an extensive framework for identifying and handling global sustainable concerns applicable to the challenges in the aviation industry as well. Although aviation is not directly involved with SDGs, the operations within the industry overlap with several goals, for example

- SDG 9 – Industry, Innovation, and Infrastructure
- SDG 12 – Responsible Consumption and Production
- SDG 13 – Climate Action
- SDG 17 – Partnerships for Goals.

These goals highlight the importance of implementing sustainable practices in industries like aviation to minimize the negative effects of the environment and ensure economic and social progress simultaneously. (Dlb, 2023.)

SDG 13 (Climate Action), focusing on urgent actions to address climate change and its consequences, imposes tremendous pressure on the aviation industry to minimize emissions while transitioning to greener technologies. It is estimated that global passenger traffic is doubled by 2040 and hence the carbon footprint increases if no responsible actions are taken (IATA 2023). To align with SDG 13, airlines and operators need to prioritize focusing on circular, resource-efficient strategies that reduce waste production and emissions, conserve energy, and promote renewable resources.

SDG 9 (Industry, Innovation, and Infrastructure) identifies the importance of sustainable innovation and industrialization, and it encourages investments on modern, energy-efficient and greener aviation operations. For instance, these investments result in SAF implementation and research, efficient engine designs, aerodynamic enhancements using light weight composite materials and renewable energy-powered airport infrastructure. One such great example is using of sustainable diesel for ground support vehicles in San Diego airport, paving the way towards sustainable aviation hubs (San Diego International Airport 2023). Aircraft manufacturers like Airbus and Boeing are using light-weight composite materials in aircraft models like Airbus A350 XWB and Boeing 787 Dreamliner to improve efficient fuel usage and minimize emissions (Airbus 2017; Boeing 2024, 6).

Nevertheless, sustainable transformation is not solely achievable by innovation unless responsible consumption and production play the role as mentioned in SDG 12 (Responsible Consumption and Production). Implementing sustainable procurement, waste management and resource optimization strategies need thorough planning by airlines. This is done by minimizing single-use plastics, providing more sustainable in-flight cuisine, optimizing aircraft operations through data analytics and automation (ICAO 2024). Proper collaboration among airlines, airports, manufacturers and regulatory bodies is essential in establishing a circular economy concept via proper system change.

In addition, SDG 17(Partnerships for Goals) is another important goal for aviation sustainability. The challenges related to light decarbonization, fleet modernization, SAF integration require strong multilateral collaboration. Global partnerships result in resources, coordinating research agendas, and integrating rules and hence increase the collective consequences of sustainability programs (EASA).

Particularly, with the guidelines provided by SDGs, the airline industry transforms these goals into detailed, quantifiable and time-specific plans. Science-based emission plans, incorporating sustainability into main business models and openly sharing the progress with stakeholders are few methods of implementing. There are appreciable initiatives within the industry that suggest this SDG integration into industry plans. The IATA's Fly Net Zero campaign is one such example of encouraging member airlines to reach net-zero emission by 2050 using a multiple strategy combination like SAF implementation, new technologies, carbon off-sets and greener operational improvements (IATA 2021). Most importantly, these types of voluntary agreements are accompanied by strong accountability systems and supportive policy frameworks.

Ultimately, SDGs is a great framework that offers a strategic roadmap in connecting aviation practices with sustainability goals. However, this sustainability roadmap occupies numerous challenges. Addressing rising air travel demand, environmental responsibility and financial feasibility simultaneously is a huge challenge. Overcoming this challenge not only needs technological innovation but also encouraging regulatory principles, global collaboration and a strong determination for sustainability from every stakeholder within the aviation industry.

# 3 Sustainable Aviation Fuel (SAF) and Fleet Modernization

## 3.1 Overview and Adoption of SAF

SAF is gaining spotlight as the key driver to reduce carbon emission in the aviation industry. SAF is produced using renewable resources such as used cooking oil, non-edible plants, algae, waste collected in cities, and carbon trapped during industrial operations. Compared with current jet fuel, SAF is capable of cutting the life cycle of greenhouse gas emissions by up to 80%, depending on the base material and production method used (Neste). SAF is easily utilized in the current aircraft engines as a “drop-in fuel” while the fuelling infrastructure is kept the same without any modifications (SKYNRG). This allows a smooth and effortless transition from fossil fuels to greener options.

Leading airlines and sophisticated airport hubs have already initiated the process of implementing SAF. Several airlines such as Lufthansa, KLM and United Airlines are flying long-haul flights powered by SAF mixes, proving that commercial aviation is now fuelled by bio-based greener options (KLM; United). Oslo Airport became the first airport in the world to provide regular SAF delivery by making it available through its current fuelling system (ICAO 2023, 1). Governments encourage these initiatives by providing policy support in the form of subsidies, blending regulations and tax reliefs.

SAF expansion is encouraged by several international frameworks. According to ICAO policies on global climate, SAF is a core component (ICAO). On the other hand, according to the proposals by the ‘ReFuelEU’ Aviation initiative by the Europe Union, it is mandatory to blend SAF in airlines operating throughout Europe (European Commission). The United States facilitates SAF manufacturers with tax incentives through the Inflation Reduction Act to reduce the price difference with fossil fuels and promote SAF production locally (IRS 2024).

Yet, the overall proportion of SAF usage is still low, according to the International Energy Agency (IEA) the value is around 0.1% by 2024 despite all these optimistic proposals. Main reasons for this low acceptance are the high cost, limited infrastructure and feedstock (IEA). Compared with traditional jet fuel prices, SAF is usually three to five times higher, causing it less affordable without government aid or productive purchase agreements (EASA).

Another limitation is the current production capacity of SAF. SAF production needs to increase at least by 70% according to EASA by 2050 to reach the goal of net-zero emission within Europe (EASA). To supplement this, significant investments are essential in improving facilities, logistics, research and development. It is crucial to have a creditable and widespread supply chain for SAF to ensure continuous supply around the world.

To encourage SAF usage in large-scale, the aviation industry needs to closely collaborate with governments, policymakers, energy corporations, R&D institutions and the public. There are some multi-stakeholder platforms like Clean Skies for Tomorrow and Sustainable Aviation Buyers Alliance by World Economic Forum elaborating the importance of such partnerships in speeding up the SAF employment (World Economic Forum 2021; SABA). Long-term purchasing agreements are getting prevalent between SAF producers and airlines, which provide financial stability to both sides and is a powerful green signal for the market.

Likewise, rather than calling SAF implementation merely a technical and financial problem, it needs a crucial strategic need for future aviation. Airlines which are the early adopters of SAF become more qualified in satisfying future emission restrictions while demanding themselves for customer expectations in a sustainability-focused market.

## 3.2 Challenges and Future Prospects of SAF

There are several challenges associated with SAF despite the potential advantages. Economically speaking, SAF is more expensive than regular jet fuel due to high production costs and restricted supply chains. High production cost is mainly due to the technologies used in current SAF production such as HEFA (Hydroprocessed Esters and Fatty Acids), Fischer-Tropsch synthesis, and Alcohol-to-jet pathways which need extensive feedstock processing and proper blending. To make SAF financially accessible, governments need to take supportive measures like subsidies, tax incentives and regulations towards SAF suppliers and airlines. (Antonenko & Hundt.)

Another main challenge is the availability of feed stock. There are several feedstock varieties available, but not all of them are sustainable. For example, palm-oil based feedstock is readily available, yet it causes issues regarding deforestation and land-use change (Transport & Environment). At the same time, water-based feed stocks such as agricultural waste and leftover cooking oil are more sustainable, but their supply is limited. It is a necessity to have future innovations on feed stocks such as algae-based, collected carbon dioxide and renewable energy powered synthetic fuel varieties. (Antonenko & Hundt.)

Maturation in technology is another challenge. ASTM International authorizes only seven SAF pathways to be implemented in commercial aviation, where majority is only permitted for a 50% blend with traditional jet fuel. Such restrictions cause SAF’s ability of decarbonization to be limited. (SKYNRG.) Hence, it is necessary to focus on innovations such as 100% SAF friendly aircraft engines and modifications.

Speaking of regulations, diverse global policies are another major challenge. For instance, even though the EU is carrying out significant practices regarding SAF blending, other regions such as Asia and the Middle East are still far behind and their SAF policies are just proposals (Transport & Environment). These mismatches create market imbalances where airlines operating in highly regulated regions possibly losing the competitive advantage until an international standard is established.

Regardless of the challenges, the future of SAF seems positive. There is evidence that technology is evolving as per the requirements and increments in both public and private investments in SAF. The Department of Energy of the United States is authorizing financing for SAF research and development as an encouragement for SAF enhancement. Further, companies such as LanzaJet and Neste are taking actions in increasing SAF production up to 10-15% of SAF by 2030 assuming that current favorable policies and investments continue.

There is a visible evolution in market demand for SAF. Passengers are keener on selecting more sustainable airlines. This increasing trend for low-emission travel encourages airlines to implement SAF more quickly, if they are supported by favorable carbon pricing or certified programs for sustainable aviation.

Overall, the journey of SAF implementation is filled with challenges, yet there’s a positive future ahead as lowering emissions is critical for future aviation. To overcome these obstacles, favorable legislation, financial investments, a network of collaborations and technological improvements are essential. (Kerster.)

## 3.3 Fleet Modernization and Alternative Energy Approaches

While SAF is a potential solution for fuel, there is another way of addressing sustainability. That is fleet modernization where existing aviation hardware, aircraft design are enhanced to minimize emissions. Further, it is possible to replace older aircraft models with technologically improved modern aircraft which are more fuel-efficient and have low emissions. According to Boeing, there is 15-25% more fuel efficiency in each generation of aircraft when compared with the previous generation (Boeing 2023). This is accomplished by using lighter composite materials, efficient engine models, improved dynamics, and advanced avionics systems.

Major airlines have already implemented the process of modernizing their fleets. Airlines such as Emirates, Qatar and Delta have made huge investments in placing bulk orders of Airbus A350 and Boeing 787 which are the most fuel-efficient aircraft models (Spray 2024; Doran 2025; Hardiman 2025). These aircraft models consider not only emission and fuel efficiency, also they are designed in a way to significantly improve passenger comfort to gain a reputation in the market. According to British Airways, Airbus A350 is 25% more fuel efficient compared to the equivalent previous models, which is a considerable contribution for a sustainable future (British Airways).

Other than acquiring new aircraft, airlines are keen on methodologies to optimize the existing fleets. Structural modifications in wings and fuselage, advanced avionics systems such as navigation and communications, advanced engine modifications and enhancements for fuel efficiency result in extending life cycle while improving the fuel efficiency (Fort Aero 2023). Additionally, there are eco-friendly operational techniques like continuous descent methods, single-engine taxiing, and improved route planning to further improve fuel eficiency (OpenAirlines 2023; Herstam 2024; SKYbrary).

Adopting digital technologies for fleet management is gaining attention now. To reduce unplanned aircraft grounding, save fuel and increase aircraft lifespan solutions such as predictive maintenance are used.  Further, analytics based on AI are also used to calculate the most efficient aircraft routing timetables while considering the weather conditions, air traffic and fuel usage. (Lu 2024.)

Aside from airplane modifications, propulsion technology is evolving. The era of electric and hybrid-electric aircraft is developing and becoming a potential solution for short-haul flights. Such examples are ‘Alice’ by Eviation and ‘Velis Electro’ by Pipistrel which are all-electric and in advanced phases of development (Eviation; Pipistrel). These are some reliable promises for the future of zero-emission, yet there are some challenges such as limited range, payload capacity and adopting them best suited for all market requirements.

Another technological advancement is hydrogen-powered aviation. Airbus is working on ‘ZEROe’, an operational hydrogen-powered aircraft launched in 2020. There is no carbon dioxide emission from hydrogen cells when they are produced by renewable energy, making it a promising solution for zero-emission and alternative for fuel-driven options. (Airbus.) Nevertheless, this technology is still in the early stages and needs further investments and supportive legislation to speed up development.

Rather than SAF being dominant, hydrogen-powered and electric propulsion gain more attention in future. By 2035, electric and hydrogen solutions dominate commuter and short-haul flights while SAF remains dominant in medium and long-haul flights and hydrogen as a supplement energy source by 2040 as explained in Table 1.

Table 1. Potential energy options for zero emission in future (4Air)

| | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|
| Commuter | SAF | Electric or Hydrogen fuel cells and/or SAF | Electric or Hydrogen fuel cells and/or SAF | Electric or Hydrogen fuel cells and/or SAF | Electric or Hydrogen fuel cells and/or SAF | Electric or Hydrogen fuel cells and/or SAF | Electric or Hydrogen fuel cells and/or SAF |
| Regional | SAF | SAF | Electric or Hydrogen fuel cells and/or SAF | Electric or Hydrogen fuel cells and/or SAF | Electric or Hydrogen fuel cells and/or SAF | Electric or Hydrogen fuel cells and/or SAF | Electric or Hydrogen fuel cells and/or SAF |
| Short haul | SAF | SAF | SAF | SAF potentially some Hydrogen | Hydrogen and/or SAF | Hydrogen and/or SAF | Hydrogen and/or SAF |
| Medium-haul | SAF | SAF | SAF | SAF | SAF potentially some Hydrogen | SAF potentially some Hydrogen | SAF potentially some Hydrogen |
| Long-haul | SAF | SAF | SAF | SAF | SAF | SAF | SAF |

Fleet modernization is thus a comprehensive plan. Ongoing enhancements in aircraft design, operations and maintenance practices result in short-term sustainability while entire transition to alternative propulsion technologies is a long-term solution.

## 3.4 Sustainable Aircraft Disposal and Recycling

Within next two decades, thousands of commercial aircrafts are retiring as they are reaching the end-of-life phase. Usually, the lifespan of a commercial aircraft is up to 30 years, yet the aircraft manufacturers determine a retirement age depending upon flight hours and pressurization cycles (JE Technology 2021). The most traditional methods used for retirement are storing in ‘boneyards’ in deserts or having their metals recovered. Since such methods are not sustainable-friendly, modern practices focus on ethical disposal and recycling methods to adhere to circular economy concepts.

Disassembly is the first step towards sustainable aircraft disposal. In this case, aircraft are disassembled thoroughly and high-priced components like engines, landing gears, avionics computers are retrieved for resale, restoration and reuse. implementing this method saves money and resources while minimizing the environmental impact of producing new components. Tarmac Aerosave, AELS and C&L Aviation Group are some reputed companies who are field experts in sustainable aircraft disassembly and ensure valuable components are back in the aviation supply chain. (AELS; C&L Aviation Group; Tarmac Aerosave.)

There are both pros and cons in aircraft recycling. The structure of older aircraft is mainly aluminium, a highly recyclable metal (International Aluminum). On the other hand, new aircraft models are mainly consisting of carbon fibre composites and titanium. Even though they are beneficial in performance enhancing, recycling of these materials is challenging (NitPro Composites). Companies such as ELG Carbon Fibre are researching viable techniques to recycle composite materials (Exel).

Environmental and legislative factors have an impact on disposal procedures. Dangerous materials like asbestos, mercury or fire extinguishing chemicals are present in older aircraft. The disposal is done according to the Basel convention which is a regulatory framework responsible for managing waste transfer across borders and providing requirements for appropriate disposal (Basel Convention).

Sustainable disposal brings both environmental and financial benefits. Field experts predict that tearing down of aircraft and reselling of components revenue to grow up to USD 14.72 billion by 2033, while opening new revenue sources for airlines and recycling service providers (Fortune Business Insights 2025). To improve the sustainable reputation, airlines commit to greener end-of-life management while complying with ESG (Environmental, Social and Governance) goals.

Ultimately, aircraft recycling as a broader sustainable initiative, and several SDGs such as SDG 12 (Responsible consumption and Production) and SDG 9 (Industry, Innovation and Infrastructure) are also fulfilled. A comprehensive perspective on sustainable aviation is not only the operation but also ethical retirement of an aircraft.

# 4 Industry Efforts and Best Practices

## 4.1 Airline Sustainability Strategies

To address environmental challenges and sustainable legislative expectations, airlines are implementing innovative sustainable practices. These practices are not merely regarding efficiency improvements but also long-term strategic planning for a sustainable future.

Finnair, the flag-carrier airline of Finland, pledges to minimize net emissions by the end of 2045. According to their plan, their older fleet is replaced gradually by Airbus A350 aircraft models which are 25% more fuel-efficient. Moreover, they are implementing single-engine taxiing, continuous descent approach landing and flight plan optimization for flights to lower the fuel combustion. Further, with a strategic approach to weight-reduction during its operations, they have implemented practices such as reducing printed documents onboard, using light-weighted trolleys and seat arrangements, and enhancing the use of potable water onboard so that when combined, they result in less fuel combustion and emission. (Finnair 2023.)

KLM Royal Dutch Airlines is a pioneer in sustainable aviation. Their concept called ‘Fly Responsibly’ highlights the shared responsibility of the airlines, passengers and other stakeholders towards the climate impact. Investments in SAF, circular economy pilot projects and promotion of substitutes for air travel/less travelling are focused on this program. Particularly, KLM promotes intermodal travel, hence they are lowering short-haul flight routes from Amsterdam Schiphol by collaborating with train operators to facilitate rail travel options for locations within 500km. (ADCN Club for Creativity 2021.)

United Airlines, whose main hub is situated in the USA, has promised to achieve completely green status by 2050, not just by depending on carbon offsetting. In contrast, they plan to invest more in SAF and carbon capture technology (United). On the other hand, the airline collaborated with a biotech firm called Viridos to expand algae-based SAF, which lowers life-cycle emissions by up to 80% (PR Newswire 2023a). This airline is a proud member of the First Movers Coalition, working together with global corporations to develop clean technology (United).

In Japan, both Japan Airlines and All Nippon Airlines are supporting the country’s goals on decarbonization. ‘Eco-First’ strategy developed by Japan Airlines focuses on fleet modernization and SAF collaboration (Japan Airlines). On the other hand, All Nippon Airlines work together with fuel developers in the region to perform demonstration flights using SAF with the objective of replacing 10% of current gasoline usage with SAF by 2030 (Neste). At the same time, these two airlines are investing in projects such as greener flight experiments like Hydrogen flights and negative emission technologies to reduce emissions (Russel 2025).

Etihad Airways is a sustainability pioneer in the Middle East, with ‘eco-flights’ performed to test emission reduction technologies like fuel-efficient climb profiles, continuous descent approach, on-ground electrical towing (Etihad 2022). Further, they implemented a program called ‘Greenliner’ upon Boeing 787 aircraft model with collaboration with companies such as Boeing, General Electric and Honeywell as an experimental environment to evaluate innovative solutions for sustainability. This program focuses on operational, technological and partnerships sectors in innovating sustainable practices for the industry (Ahlgren 2021).

Alaska Airlines is a sustainable pioneer in North America. In 2016, this airline initiated the world’s first commercial flight using forest residual SAF. The airline’s current goal is to reach carbon emission neutrality by 2050. (Alaska Airlines.) In 2023, the airline utilized a software called ‘Flyways’ to use AI to route optimization, from which it saved over 1.2 million gallons of jet fuel (Lyngaas 2024). Further, there are sustainable practices implemented in the cabin such as promoting 92% plant-based cups by abolishing single-use plastic cups, becoming the first in the USA to replace plastic with paper-based alternatives (PR Newswire 2023b). This airline repeatedly ranked in top of the Dow Jones Sustainability Index, by suggesting that even medium-sized airlines have an impact within the industry for a sustainable future.

The examples above indicate efforts by airlines to reach sustainability goals via various implementations such as adapting to a greener fleet with modifications and investments, efficient operations and stakeholder collaborations.

## 4.2 Passenger Engagement and Carbon Reduction Initiatives

A passenger is an important stakeholder responsible for the future of sustainable aviation. Airlines are working on a variety of technologies, reward plans, and instructional initiatives to encourage passengers towards carbon reducing practices while maintaining trust and comfort of the customers.

Lufthansa Group has a carbon compensation function in their ticketing system, which permits passengers either to offset their portion of emission via certified climate initiatives or pay for the use of SAF (Lufthansa). The airline implemented a ticket option called ‘Green Fares’ in 2023, that charges additional funds contributing directly to environmental protection projects. There is a portal owned by the airline called ‘Compensaid’ indicating environmental impacts to the passengers by their journey and options to minimize individual carbon footprint by suggesting SAF purchasing options. (Lufthansa Innovation Hub.)

In 2020, Air France implemented a policy covering their entire domestic flights to automatically offset carbon, where the cost was handled internally. With regards to the long-haul flight passengers, the airline provides a well-structured offset scheme enabling passengers to involve with forest conservation and renewable energy projects (Orban 2019). Other than that, the airline initiated promoting sustainability content in their inflight entertainment system and offering QR codes to help passengers to adopt further greener travel habits.

Qantas Airline which is the flag-carrier airline of Australia owns a program called 'Fly Carbon Neutral' which is one of the world's largest airline offsetting schemes. Passengers have the chance of offsetting their travel during online booking, and the airline is committed to match every contribution dollar-for-dollar. In 2023, a sustainability dashboard was introduced in the mobile app by the airline so that every passenger examines their emissions, monitor reduction of carbon over time, and to collect Frequent Flyer points by participating in sustainable initiatives. (Qantas Airlines.)

Singapore Airlines owns a voluntary carbon offset program and is used to reward KrisFlyer members with miles when they contribute to the environmental projects. Using this offset program, the airline funds the clean energy initiatives that are performed in Asia and the forest conservation activities in the African region. (Surgenor 2021.) These actions not only appreciate the environmental-friendly passengers but also encourages other passengers to make small behavioural changes that impact largely on nature.

Cathay Pacific's 'Fly Greener' program allows passengers to offset aircraft carbon emission while booking and these funds are directly invested in verified Gold Standard projects. In 2024, they initiated a strategy to reward passengers who offset carbon or fly SAF-blended flights with Asia Miles and allow passengers to follow their carbon savings on a dashboard of the app. At the Hong Kong international Airport, the airline initiated a program called 'Green Departure' which encourages passengers to pack low weights, recycle their own onboard waste, and choose low carbon meal options suggesting that these simple behaviours lead the path to emissions reduction. (Cathay Pacific 2024.)

In summary, these examples by the airlines indicate the importance of educating and encouraging the passengers towards carbon offsets, SAF-blended travelling and other behavioural patterns towards sustainability. Airlines are working on developing interactive, inspiring and informative programs to engage their passengers actively towards decarbonization. While these strategies improve positive environmental impacts, they further amplify the customer satisfaction and loyalty towards the airlines.

# 5 Discussion

## 5.1 Background Analysis

Based on the research data in chapter 1 – 4, sustainable aviation is making great progress in legislative perspective, technological innovation, operational planning and passenger involvement. However, the pace of transformation is slower in adapting industry into climate goals of reaching net-zero emissions by 2050.

Aviation industry is solely responsible for 2-3% of global carbon dioxide emission, further wide-body aircrafts are the main emitter responsible for 57% as mentioned in chapter 2. This emphasizes the importance of focusing on long-haul flight operations through practices such as SAF implementation and fleet modernization as in chapter 3.

Aviation sector broadly focuses on SDGs, especially SDG 13 (Climate Change), SDG 12 (Responsible Consumption and Production), SDG 9 (Industry, Innovation, and Infrastructure) and SDG 17 (Partnerships for Goals). Discovered challenges belong in those SDGs and responsible parties are working on resolving them.

## 5.2 Core Decarbonization Strategies Analysis: SAF and Fleet Modernization

The transition to a low-carbon future is strongly dependent on two main strategies: SAF implementation and fleet modernization. Based on chapters 2 and 3, these measures are the current most plausible near and medium-future alternatives to reduce carbon lifecycle emissions. There are other possible alternative propulsion technologies such as electrical and hydrogen that are still in the early stages of research.

SAF is identified as a potential solution for decarbonization in long-haul flights until the implementation of electric and hydrogen technologies. As discussed in chapter 3.1, SAF has the potential to reduce carbon dioxide emissions by up to 80% and it is compatible with current engine infrastructure without major modifications that enables easy implementation. According to IATA reports referred to in this thesis, most airlines are already implementing SAF blending in their daily operations (IATA 2023).

According to IEA SAF is used for less than 0.1% of total aviation fuel consumption (IEA). According to the findings, the main reasons for poor adaptation are high production cost due to feed stock limitations and limited infrastructure capacity. SAF pricing is two to five times higher than jet fuel says EASA (EASA). As explained in previous chapters, governments are taking measures to minimize these economic restrictions through legislations such as the Inflation Reduction Act in the United States that provides tax incentives to SAF manufacturers and the ReFuelEU initiative in the EU which demands a minimum SAF blending levels by 2030. However, the absence of uniform international policies threatens global scalability. As thoroughly analyzed in Chapter 2, region-wide multiple regulatory frameworks cause uncertainty for airlines and investors resulting in production delays and cross-border distribution of SAF.

Fleet modernization is the other potential solution for decarbonization. According to Airbus and Boeing, new aircraft models such as Airbus A350 and Boeing 787 Dreamliner are designed to achieve more fuel efficiency, about 20-25% than previous models. These aircraft compromise light-weight composite materials, improved aerodynamics and efficient engines directly impacting fuel combustion. According to chapter 3.3, British Airways, KLM and Finnair have proven operational efficiency rise due to fleet modernization. Furthermore, SAF implemented in modern aircraft as a coordinated strategy is more efficient and greener.

Advanced operational techniques are amplifying above-mentioned success. AI powered systems are now used to optimize flight routes, save taxiing time, forecast maintenance necessities in airlines such as Lufthansa, Singapore Airlines and many more. Furthermore, as per chapter 3.3, most of the airlines utilize efficient practices such as continuous descent approach, single-engine taxiing and enhanced air traffic coordination to minimize emissions during operational phases. These improvements are significantly important since these implementations don’t need large financial investments and complexities.

Nonetheless, there are challenges and limitations associated with SAF implementation and fleet modernization despite being potential solutions. SAF is expensive due to limited feed stock while fleet modernization requires a huge investment which most of the small and medium-sized airlines cannot afford. On the other hand, SAF blending is majorly implemented in North America and Europe while there are some regions, with no initiatives yet. Likewise, developing economies, aging aircraft and inadequate environmental laws cause challenges in implementing these strategies.

Most importantly, SAF and Fleet Modernization aligns with the elements of theoretical frameworks discussed in chapter 1. The Diffusion of Innovation Theory identifies SAF adoption in sequential patterns within the industry, where early adopters are often encountered in the market with legislative incentives and strict environmental standards. Likewise, fleet renewal and disposal align with the Circular Economy framework where recycling aircraft components and aircraft disposal become greener as explained in chapter 3.4.

Nevertheless, several recent regulatory and political changes highlight the importance of promoting SAF. The upcoming Green Claims Directive (GCD), a national law by the EU in 2026, restricts airlines depending merely on carbon offsetting and needs to adopt concrete practices to brand airlines as environmentally friendly. Hence, this GCD encourages airlines towards SAF and fleet modernization.

For example, Finnair faced criticism for claiming their SAF adoption reduced carbon emission without mentioning that accounted SAF was only a small volume of total fuel used. Finnair had to eventually withdraw this advertisement. This is an ideal explanation of reputational damage due to greenwashing and emphasis on the importance of airlines to strengthen their sustainability claims with verified and detailed initiatives. To comply with GCD regulations and public satisfaction, airlines need communication regarding carbon reduction initiatives more accurately and responsibly in the future.

To summarize, SAF and fleet modernization are the fundamentals of decarbonization roadmap in the aviation industry. Even though there are significant results in emissions reduction, their success mainly relies on legislative support, financial investments, cross-sector relationships, technological innovations and investments on ongoing projects. Electric and Hydrogen technologies are future trends, however, until they come into action SAF and fleet modernization are the most feasible applications to minimize climate and environmental impact for at least the next two decades.

## 5.3 Regulatory and Strategic Challenges Analysis

The sustainable future of the aviation industry depends not only on technological innovations and fuel solutions, but also on effective regulatory frameworks for the environment as well as corporate operations. According to the findings in chapters 2 and 4, environmental regulations, sustainability plans of airlines and passenger involvement are immensely influencing a greener approach.

Global regulatory frameworks such as ICAO's CORSIA and EU ETS are the structural basis for emission control. Yet, according to the data referred, these frameworks have certain major limitations. CORSIA is still voluntary in its early stages, so far only 126 out of 193 ICAO member states adhering to it by 2024, which limits the worldwide effectiveness. (ICAO 2024.) Moreover, CORSIA is highly dependent on offsetting mechanisms rather than carbon emission reductions and is raising doubts about its long-term effectiveness. Additionally, the EU ETS being stricter, is only applicable for intra-European flights, resulting in scattered markets and different regulatory requirements across the region.

These regulatory mismatches disturb the uniform global industry establishment. Referring to chapter 2, airlines with weak policies towards the environment delay the SAF implementation, fleet modernization and aircraft replacements since they are neither wronged nor encouraged. There are counter actions towards sustainable goals in the aviation industry.

The research findings depict the importance of establishing a uniform global regulatory framework towards SAF implantation standards, emission restrictions, fleet modernization and renewal.

According to chapters 3 and 4, airlines are increasingly adopting sustainable practices into their operational strategies. Some major airlines are allocating large funds to SAF implementation, fleet modernization and research and developments. On the other hand, airlines like United Airlines and Etihad Airways have negotiated future purchase agreements for SAF and the new fleet, adopting financing decisions towards sustainable targets indicating that environmental considerations are now directly influencing financial arrangements.

Nevertheless, these commitment levels among global airlines differ significantly and cause non-smooth transitions. Larger airlines with strong financial capabilities and organizational capacity become early adopters of SAF implementation and fleet modernization. On the other hand, smaller or medium-sized airlines are struggling to adapt due to high cost and strict regulations. Therefore, an inequality in market competition arises where sustainability acts as a factor that differentiates the market rather than uniting the market with uniform standards.

Another strategic approach used by airlines is passenger involvement. Basically, it is a tool of restricting behavior since passengers are also responsible stakeholders in this roadmap. According to chapter 4.2, most of the sustainably adopted airlines have implemented carbon calculators where passengers calculate the amount of carbon dioxide they save, offset programs they decide to fly with less emissions, and reward programs to encourage passengers to integrate sustainable practices in their travel plans. However, acceptance from the passengers is ambiguous. For example, many criticisms are arising against voluntary carbon offset programs as it makes passengers feel guilty for their actions and as a result passenger engagement for this program takes a low value around 1 - 3% of the entire passenger population (Air Transport Action Group 2020).

Furthermore, the forthcoming GCD in 2026 by the EU focuses on governing environmental marketing. Airlines need to strengthen their sustainability pledges with verifiable and continuous actions, other than solely depending on carbon offsetting. This directive is an eye-opener for airlines in reevaluating their current practices and encouraging them to invest more in SAF and fleet modernization.

In addition, airlines prioritize releasing annual sustainability reports emphasizing their work for a greener future and frameworks such as the Global Reporting Initiative (GRI) and Science-Based Targets initiative (BSTi) yet doubts regarding transparency and reliability on environmental commitments are arising. As per the Transport & Environment article, there are offsetting schemes which are not verifiable, and many carbon reduction claims last unchecked. In this case, strong third-party supervision is essential, unless the stakeholder trust and credibility fade over time.

To summarize, the interconnection of regulatory frameworks, business strategy and passenger involvement indicates progress as well as current deficiencies. Even though individual efforts are encouraged, systematically coordinated efforts are still lacking in the system. To achieve sustainability goals as an industry, uniform regulations, and transparent reporting to the public, inclusive customer tactics are needed to synchronize work. Without these collations, the greener goals diminish over time.

## 5.4 Synthesis of Critical Research Findings

According to the details and evidence from chapter 1-4, the aviation industry is making progress towards the sustainable goals, however, the rate and the magnitude of the efforts are not sufficient to reach the net-zero emission goals by 2050. SAF blending is a promising solution, yet its usage is still limited to 0.1%. Further, new aircraft models like Airbus A350 and Boeing 787 Dreamliner are becoming great solutions for carbon reduction since they are 25% more efficient than previous models. On the other hand, modifications on existing fleets result in significant benefits, possible engine solutions like hydrogen and electric are still some decades away for commercial flights.

Lack of universal regulatory frameworks is a critical issue. Even though there are frameworks such as CORSIA and EU ETS, they are only applicable to certain regions and operations where there is no encouragement towards the entire aviation sector in adhering to sustainable requirements as per the ICAO report.

Additionally, Passenger involvement is not at the expected level even though the airlines are improving sustainable operational strategies to encourage their passengers. Participation in the voluntary offsetting program is considerably low, suggesting a gap between the actions taken by the airline and passengers’ motivation to adhere to them.

Overall, the research demonstrates that initiatives by the aviation industry towards a greener future are real and advancing, however they are not sufficient to reach climate goals. Without sufficient regulations, collaborations, SAF establishment with easy accessibility, and increased passenger involvement, the zero-emission goal is a long process to achieve.

# 6 Recommendations

## 6.1 Recommendations Overview

Referring to chapter 5, a list of the best practices and recommendations for simultaneously achieving sustainability and operational profitability are included here. These suggestions are based on current trends in the industry, previous academic research and sustainable goals of the international organizations. These proposals guide in reducing the gap between the current practices and the planned achievements with effective participation and collaboration between airlines, regulatory bodies, SAF manufacturers, and technology developers. Here, the listed practices and recommendations are focused on the capability despite the size of airlines.

## 6.2 Operational and Technological Best Practices for Airlines

- Lifecycle-Based Fleet Modernization Strategy

Based on chapter 3.4, rather than solely considering new aircraft purchases, airlines need to focus on a modernization strategy based on aircraft's life cycle. Upgrading existing fleet with less fuel consuming and high fuel-efficient technologies instead of current fuel technologies, substituting high consuming components with new models of better performances, retiring old aircraft according to the end-of-life sustainably practices like component harvesting and material recycling.

- Performance Optimization through Prediction Using Digitalization

Based on chapter 3.3 and examples from Lufthansa and Singapore Airlines, AI and machine learning technologies implemented within airlines improve the efficiency of operational platforms by route optimizing, continuous monitoring of aircraft health, forecasting fuel usage using real time data, and predictive maintenance. These implementations result in increasing fuel efficiency with low emissions and more savings. Further, predictive maintenance is beneficial for effective maintenance scheduling resulting in less wastage and longer airworthy lifespan of an aircraft.

- Improved Cabin and Ground Efficiency

Remodeling the aircraft with composite materials to make cabins lightweight and using environmentally friendly service carts is simple yet an effective practice. According to thesis examples, Finnair and Emirates have proven to lower emissions by implementing these practices of lowering cabin weight in their flights. When on-ground, implementing practices such as single-engine taxiing, electric towing, and less auxiliary power unit (APU) usage, it is possible to reduce emissions, thus net emissions of an aircraft is minimized.

- In-house Sustainability Training for Engineers, Flight Crew and Ground Staff

Integrating sustainability training into operational teams, pilots to ground staff ensure everyday practices are aligned with emissions goals. Tailored training for pilots, engineers and ground staff regarding fuel efficient flight strategies such as continuous descent approach, minimized APU usage, SAF handling and efficient maintenance planning, while proper waste sorting, recycling and in-flight sustainability for cabin crew incorporate an updated working environment for employees regarding the company sustainable goals.

- Strategic Implementation of SAF

Most of the airlines are reluctant for SAF blending due to high cost and less availability. Airlines without SAF implementation are encouraged for gradual adoption by introducing a small value around 5-10% SAF blending at the beginning for long-haul flights and then eventually increasing the amount of SAF to all flights despite the distance. Logistics issues are addressed by airlines creating partnerships with SAF manufacturers and distributors, just like the Oneworld Alliance’s joint procurement agreements for SAF.

## 6.3 Sustainability Strategies Towards Passengers

- Green Rewards Programs

Developing a loyalty-based reward program to compensate passengers selecting low-carbon travel options is an encouraging strategy by airlines. According to chapter 4.2, such programs are already implemented in larger airlines such as Singapore Airlines and Qantas Airways. On the other hand, most airlines are not implementing these practices. Hence, encouraging customers is needed by airlines to choose greener options when tickets are booked.

- Carbon Transparency When Purchasing

Updating the existing booking platforms of the airlines with a carbon calculator where customers are acknowledged about the carbon capacity emitted or reduced by their selected flight and greener options such as SAF contributions and carbon offsetting. This approach encourages customers to make thoughtful decisions about sustainable travelling.

- Eco-branded Ticket Options

According to Lufthansa examples and their strategy called ‘Green Fares’, launching a category of eco-branded tickets by airlines consisting of SAF donations, carbon offsetting and bonuses into a single transaction encourages customers. This strategy amplifies the airline’s reputation as a responsible brand in the market rather than reducing emissions to the environment.

- Educational Campaigns About Sustainability

Incorporating creative and educational content such as sustainable travelling, SAF stories, and personal impact on dashboards into in-flight entertainment systems, airport displays and mobile apps encourage passengers to consider sustainability when making decisions. This practice is already implemented in some major airlines and expanding to all airlines results in positive outcomes.

- ‘Slow Travel’ Campaigns for Short-Haul Travel

Airlines and railway companies have the opportunity of collaborating to provide blended air-rail travel packages for domestic and regional flights. Promoting trains for short distances minimize carbon emissions while preserving air resources for long-haul transportation.

## 6.4 Policy Recommendations for Governments and International Bodies

- Compulsory SAF Blending Requirements with Flexible Options

Setting up government regulations to impose minimum SAF blending requirements, for example, a compulsory requirement for all airlines for minimum 5% of SAF blending by 2030, gradually establish SAF implementation on global scale. However, these regulations need flexibility unless small and medium-sized airlines face difficulties in adopting. Such flexibility options offer SAF credits to partners based on the amount of SAF consumed and banking excess SAF for future adherence.

- Green Taxation and Revenue Recycling

Instead of standard carbon emission taxation, the best practice is to combine taxes with aviation-related green taxes based on R&D investments, SAF infrastructure and low-emission aircraft incentives. Such taxes and refund mechanisms make certain that airlines reach sustainable targets while the business remains profitable. Additionally, these revenues are used as transitional funds for small-sized airlines when emerging markets.

- International Certification for Carbon Reporting

To resolve the gaps in sustainability among airlines across regions, introducing a carbon emission certification system by international regulatory bodies such as ICAO and IATA is essential. By doing this, airlines are persuaded to report their emissions, SAF implementation, and carbon offset performances according to standardized parameters. This amplifies reliability and transparency for investors, customers and other stakeholders.

- Encourage Innovation Projects and SAF Hubs

Encouragement from governments is needed for SAF innovation projects including SAF manufacturers, investors, researchers and airlines. These projects accelerate SAF R&D and reduce the chance of commercialization by combining infrastructure facilities, feed stock resources, supply chain and logistics.

- Aligning National Policy with EU's GCD

National policies need definite consequences of GCD for aviation as it goes into effect in 2026. Mere carbon offsetting techniques are no longer acceptable, and airlines need to demonstrate significant emissions reductions. To sustain, clear instructions and implementation methods are required.

## 6.5 Financial and Market-Based Solutions

- Sustainability-Linked Financing

Encouraging Airlines to use sustainable bonds and loans providing interest rates based on proven ESG performances such as SAF consumption targets and carbon footprint reductions. Etihad Airways' sustainability linked Sukuk highlights the way such a model captivates the interest of investors while being responsible for capital flows (Ravindirane & Jan 2020).

- Restructuring Voluntary Carbon Market

Governments and non-government organizations (NGO) work together to ensure standardization, and quality of carbon offset initiatives implemented by airlines. Airlines support only the compensation schemes that are verified by trusted institutions such as Gold Standard and Verra and are transparent in the allocation of funds (Carbonibus 2023). Since SAF implementation is growing, it is essential to restore trust in the voluntary market for short-term climate change solutions.

- Green Purchasing Groups

Airlines forming purchasing alliances to pool SAF demand, reduce costs and strengthen supply networks. To mitigate the risk of initial investment, these pools are backed by governments or banks-supported guarantee funds. If airlines act together rather than individually, they impact on SAF purchasing prices and the impact is huge.

## 6.6 Recommendations for Cross-Sector Collaboration

- Airline - Airport Collaboration for Efficient Infrastructure

Collaboration between airports and airlines significantly improves operational efficiency and greener practices. Reduced taxiing time, collaborative digital ground handling, SAF distribution pipelines and connected electric charging systems for hybrid or hydrogen-fueled aircraft are the shared goals of these two sectors. As mentioned in the thesis, Schipol Airport and Changi airport are playing pioneer roles in embracing these practices.

- Academic - Industry Collaboration for R&D

Universities and research institutions collaborate with airlines to initiate projects and experiment with new technologies such as hydrogen and electric refueling, AI based emission prediction, SAF production using carbon dioxide, etc. Not only the technologies, projects regarding operational efficiency and strategic planning are also potential projects within the universities and airlines investing in those projects. Such collaborations boost innovation, support students to get exposure to real-life business world whereas lowering costs and legislative constraints.

- Knowledge Sharing by Airline Alliances

Rather than confronting commercial partnerships, the alliances such as oneworld, Star Alliance are capable of establishing sustainability cooperation by exchanging emissions data, offset techniques, SAF resources and legislative strategies. These inter-alliance sustainable goals improve collaborative impact and integrity.

## 6.7 Strategic Outlook Summary

The aviation Sector has got two options. They either treat sustainability as a promotional agenda or accept it as a major transformational tool for the future. In this chapter, the proposed recommendations and best practices to address operational, legislative, financial and collaborative perspectives command a greener future faster and easier.

When proposing these ideas, practicality of the ideas was considered, and they are based on existing practices and flexible policy approaches. Yet, time is a crucial factor. To achieve emission targets by 2030 and 2050, these practices need to be implemented as soon as possible with proper management, policies and collaborations.

# 7 Conclusion

## 7.1 Answers to the Research Questions

**Main Question: How do sustainable fuel partnerships and fleet modernization contribute to a sustainable approach towards future aviation?**

Incorporating SAF partnerships and fleet modernization are critical to the aviation industry's transformation into low greenhouse gas emissions. These two strategies reduce the major emission sources of the industry, which are traditional jet fuel usage and aging fleets resulting in operational efficiency, greener energy deployment and long-term sustainability.

SAF partnerships are encouraging carbon emissions reduction. These SAF logistics are expanding in terms of capacity and price by partnering with airlines, airports, fuel suppliers, and governments. As mentioned in chapter 3, current SAF utilization is below 0.1% of the global aviation fuel consumption. Nevertheless, corporate partnerships like Lufthansa and Neste, United Airlines and World Energy are beginning to overcome feedstock availability, processing capacity, and supply chain. Such partnerships imply that the market is ready and minimize investor risk. The ReFuelEU project in the EU mandating airlines to increase SAF blending ratio from 2% in 2025 to 70% in 2050, influence these SAF partnerships to be compulsory rather than voluntary. Without these partnerships with stakeholders, airlines face regulatory breaches, negative brand image and operational delays.

On the other hand, fleet modernization supports decarbonization by either replacing or modifying the older, low fuel-efficient aircraft models with more aerodynamically advanced aircraft models and techniques which consume fuel efficiently. For example, new aircraft models such as Airbus A350 and Boeing 787 Dreamliner are 25% more fuel efficient than previous aircraft models. Further, incorporating sustainable design enhancements has proven results in less emissions by implementing composite materials, winglets, and hybrid-electric propulsion methods to current aircraft models. Yet, there are significant limitations due to high costs, long development and manufacturing cycles and long queues for aircraft delivery.

Most importantly, the combination of SAF partnerships and fleet modernization delivers a system-wide strategy for the green aviation industry. Both strategies are insufficient on their own. Replacing and modifying aircraft without SAF results in dependency on fossil fuel while implementing SAF without fleet modernization hinders fuel efficiency. These strategy combinations facilitate less greenhouse gas emissions, harmony with sustainable regulations and increment in public acceptance.

Going forward, standardizing these strategies through carbon accounting procedures, SAF credit systems and uniform global regulation systems encourage international fuel certification and fleet lifetime monitoring. Moreover, providing subsidies, green financing and upgraded infrastructure by governments and international parties encourage these practices.

**Sub-question 1: What are the key challenges and opportunities in implementing SAF into airline operations?**

Implementing SAF into everyday airline operations is challenging in both technological and economic aspects. Further, there are barriers in production, regulations, cost and public reputation.

The key challenges in implementing SAF are:

- High cost and limited supply

Purchasing SAF is 2-5 times more costly than traditional Jet A1 fuel. Further, production is limited due to the scarcity of feedstock materials such as cooking oil, city-collected solid waste, and algae. Without flexible directives and requirements, not all airlines have financial capability to afford required SAF blending percentages particularly with the low profit margins after the COVID-19 pandemic.

- Lack of infrastructure

Since SAF is ‘drop-in’ ready, it is compatible with existing aircraft engines and fuel systems without modifications. However, airports lack adequate distribution infrastructure. This hinders the typical refueling process and causes difficulty in the logistics process. This is a significant issue for long-haul flights when SAF refueling is not available at the destination airports.

- Different regulations across regions

There are no standard international regulations on SAF certification and blending impacts every airline. The EU leads the sustainable approach with ReFuelEU and upcoming GCD and the USA through tax incentives. However, there’s no specific SAF policy in Asia, Africa, and Latin America. Such differences cause complexities on long-haul flights with SAF blending, since they don’t comply with the SAF standards of destination airports. Due to such concerns about market access, there is a hindrance to investments in international SAF infrastructure.

- Lack of standards for emission accounting and verification

Despite being advertised as a low emission alternative, the life cycle emissions of SAF vary notably with the used feedstock material and the production process. Since there are no standards in calculating emission life cycle values and certification requirements, airlines and SAF providers depend on different and overstated emissions values. This causes a threat to the public image, especially under the regulatory influence such as upcoming GCD in the EU which expects verified and evidence-based sustainable claims.

There are current opportunities, and they are improving. They are as follows:

- Support from the EU policies

ReFuelEU regulations establish a steady demand curve for SAF manufacturers and encourage investments by enforcing minimum SAF blending percentages. Further, the EU ETS setting up carbon pricing is also encouraging SAF implementation within the EU.

- Early-adopter support

Active adaptation of SAF establishes a competitive advantage and stakeholders trust in the airline. For instance, Lufthansa, being an early adopter of SAF implementing, established the airline as a pioneer in sustainability within Europe. Early adopters have the power to influence policies, secure limited pre-orders, and improve brand loyalty. Further, airlines that integrate SAF into their long-term planning distinguish the brand from competitors within the market where climate concerns are growing.

- Technological advancement and feedstock innovation

SAF production processes are gaining rapid advancements and broadening the availability of feedstock materials. Newly innovated feedstock materials such as algae and captured carbon dioxide increase the sustainability and long-term adaptability of SAF. With these technological advancements and innovations, SAF production becomes less costly, scarcity and supply chain challenges are withdrawn.

- Development of SAF credit trading system

With the increase in SAF usage, developing an SAF credit trading system is gaining fame among the airlines. Through this system, airlines which consume SAF than the standard measurements get the opportunity to either exchange excess credits or reserve them for future fulfillment. While still in development, this system replicates the success of carbon credit schemes when managed properly.

**Sub-question 2: How does fleet modernization enhance fuel efficiency and minimize greenhouse gas emissions in aviation?**

Fleet modernization is simple, yet it is very successful in reducing fuel consumption and greenhouse gas emissions. As discussed in chapters 3.3 and 5.2, newer aircrafts have improved features in engine systems, aerodynamics and less weight due to composite materials. These aircraft models are 25% more fuel efficient than the previous aircraft models. This efficiency is crucial for long-haul flights since they are the biggest contributors to emissions. The Airbus A350 and Boeing 787 Dreamliner are built with raked wingtips, reduced drag and more fuel-efficient engines such as GTF and LEAP series models. Other than these, digital optimization also benefits fleet modernization via predictive maintenance and route optimization to minimize the fuel consumption during operations.

Nevertheless, fleet modernization has challenges. High expenditures for new aircraft acquiring and existing fleet modification is the main challenge especially for small and medium-sized airlines. Even though there are green financing and leasing options, it is not sustainable without regulatory support. Further, proper disposal and recycling of older aircraft and components following the circular economic principles is important in reducing the negative environmental impact of fleet modernization.

New aircraft models are equipped with technologies that suffice for the regulatory requirements of the present and future such as SAF compatibility and increasing SAF thresholds. With the ability to adopt high SAF volume, these models achieve certification requirements for fuel alternatives and electric-hybrid technologies. Likewise, fleet modernization alone supports low emissions while improving SAF implementation ability. However, technological advancements are still in process and electric-hybrid technologies are two decades away. Therefore, airlines follow a long-term plan on fleet modernization today to prepare for future technologies.

In the end, fleet modernization requires huge investments in finance and resources yet provides significant amplifications in emission reduction and efficient operations. Combined with SAF and regulations, fleet modernization speeds up the industry’s mission of net-zero emissions.

## 7.2 Future Research Directions

According to the findings of the research there are several knowledge shortfalls in the roadmap of aviation sustainability, especially regarding SAF deployment, fleet modernization, legislative uniformity, infrastructure advancements and passenger involvement. These shortfalls provide guidance for future research for a smooth aviation transition to a greener future.

Despite the recognition that SAF has the potential to minimize life cycle emissions by up to 80%, operational integration is still limited. Expanding SAF usage relies on thorough research regarding techno-economic feasibility of production processes such as electro fuels, algae-based fuel, and city waste-to-fuel processes. Comparative studies across geographic regions reveal the differences in feed stock availability, production cost inputs, and climate adaptability. These differences impact directly on expandability and hence regional studies are important in developing optimal and regionally acceptable SAF production processes.

In addition to industrial methods, the availability and sustainability of feed stock materials are often overlooked. Since the global demand for land and agricultural resources are increasing, future SAF production processes need a balance between trading off food energy, water utilization, and land availability. Research on the feasibility of SAF production materials in relevance to climate change is critical in assessing long-term supply capacity. Moreover, assessment of environmental impacts due to land use change and indirect emissions is essential using standard life cycle assessment methods which are currently not uniform across regions.

Logistics remains a challenge for integrating SAF into flight operations. Majority of the airports are not yet prepared for the blending and distributing of SAF into the flights. Empirical research on airport's ability on storing capacity, blending equipment and approval processes is essential in encouraging infrastructure investments. Regional logistics strategies that enable reducing transportation emissions whilst increasing cost efficiency are not yet developed. Research on such developments supports optimizing SAF supply chain in terms of geographically remote or limited-resourced situations.

Another important aspect requiring further research is the lifecycle monitoring of SAF. With more emphasis on transparency due to regulations such as the EU's GCD, there is a need for effective methods of verifying SAF content and monitoring emissions throughout the fuel life cycle. Digital platforms such as Blockchain are potential solution providers, but they haven't been widely adopted and reviewed. Further study on SAF life cycle monitoring systems and their regulatory aspects is crucial in ensuring precise carbon reporting and compliance with regulations.

Fleet modernization is a complementary approach for SAF implementation, yet its environmental impact over its entire life cycle has not been fully studied. Even though modern aircraft and modifications improve fuel efficiency and minimize emissions, existing regulations either do not or rarely cover the emissions resulted during manufacturing of aircraft and other environmental impacts during recycling. Integrating circular economy principles into fleet renewal requires research into adaptable aircraft design, component reuse, and sustainable dismantling procedures. An economic and environmental assessment of aircraft recycling opportunities in emerging markets help in expanding global accessibility to sustainable fleet transformation strategies.

Regulation uniformity is a critical challenge in governing aviation sustainability. Even though existing frameworks such as ICAO's CORSIA and EU ETS provide guidance, there are differences in SAF implementation definitions, accounting practices, and emissions standards leading to misunderstandings across regions and resulting in inefficiency. Research on comparison between regional and international regulations lead towards more uniform policies. In addition, since the environmental claims are subject to increased surveillance under directives and investor demands of ESG accountability grow, it is essential to investigate the effectiveness of third-party verification mechanisms in verifying emissions claims.

From SAF donations during booking to introducing eco-friendly flying options, passenger involvement strategies are becoming increasingly popular among airlines, however its actual impact on passenger behavior is little known. Future research on the success rate of these strategies from behavioral and economics perspectives benefit airlines in identifying optimal ways to involve passenger decisions. Further, regional and cultural aspects impacting environmental perspectives are lacking research although it is an important attribute in international operations.

Research on future-oriented developments on engine propulsion systems is critical for aviation R&D. Hydrogen and electric-powered propulsion systems are in early stages of development and viability studies on these are ongoing. Further technical research on designing fuel cells, battery weight and systems integrations are essential in determining a timeline for a commercially viable aviation sector. In addition, detailed modeling encompasses cost conditions, infrastructure demands, regulations, and route operativity help in preparing for long-term transformation away from SAF and fossil fuels in the next decades.

Aviation sustainability is linked with labor and social elements as well. However, most of the current research is focused on technological advancements, emissions and operational strategies where less emphasis is on social and workforce factors. Research on the workforce impacts on SAF infrastructure, sustainable production and improved maintenance practices help in guiding labor growth and adaptive training strategies. Moreover, regulated research on financing strategies, especially for small and medium-sized airlines promote equality in accessing sustainable aviation. Thorough research on such system inequalities benefits in improving worldwide access to SAF facilities, fuel-efficient modern flights and sustainable advancements.

To conclude, the future of aviation sustainability depends not just upon upgrading current technologies but also on bridging knowledge shortages in supply chain, behaviors, regulatory frameworks and equal accessibility. The following stage of aviation research requires a multi-phased strategy including engineering, economics, environmental studies and legislative evaluation. The topics discussed in this thesis reflect key research areas that are closely related to the industry's strategic goals, stakeholder demands and environmental obligations.

## 7.3 Validity and Reliability

**Validity**

This thesis ensures validity by addressing the objectives and research questions defined from the beginning. The study evaluated the contribution of SAF partnerships and fleet modernization towards sustainable aviation which were the primary topics of chapters 2-6. The conclusions are relevant and conceptually established by utilizing secondary data, industrial case studies and existing theoretical frameworks such as Innovation Diffusion Theory and the Circular Economy Model.

Regards to validity, the recommendations and findings of this thesis are applicable to a majority of global airlines and regulatory circumstances of the aviation industry. Further, specific evaluation is done on real-world airline cases such as Lufthansa, Singapore Airlines, United Airways, and Finnair for broader insights regarding challenges of SAF implementation and benefits of fleet modernization under different regional and regulatory situations. Based on the identified trends and common operational practices, the recommendations in chapter 6 are applicable for the general aviation industry rather than specified towards specific cases. Moreover, future policy modifications like the EU's GCD and SAF blending requirements are considered in this study to amplify the validity.

**Reliability**

The reliability of the study is supported by the usage of reliable and publicly available secondary data resources including sustainability reports of major airlines, academic papers and international legislative documents. The research is following a clear analytical procedure in analyzing gathered data throughout the chapters. This evaluation is consistent with the usage of clear sources and transparent methodological systems throughout the study.

Even though the scope of this research is not up to primary data collection, the transparency of the secondary data sources and methodology allow other researchers to replicate the results in similar criteria. In addition, integrating data from different types of sources such as airline strategies, regulatory evaluations and industrial strategies amplify the reliability of derived conclusions. Also, using case studies representing every continent further strengthens the recommendations and conclusions as they are based on a wide range of industrial events.

Ultimately, this study is a reproducible and evidence-based assessment of the current and future sustainable aviation roadmap. Precise methodologies and coherent theories implemented in this study make it a reliable platform for future academic research and policy assessment.

## 8 Summary

The aviation industry is crucial in connectivity and economic development around the world. However, it is one of the most polluting industries, especially air pollution. Increment in environmental issues, regulatory restrictions and public awareness are driving the industry into a more sustainable approach with the goal of reaching net-zero emission by 2050. This thesis is focused on the two most important strategies leading the green pathway, which are SAF partnerships and fleet modernization.

This study combines existing literature with industrial case studies to explore the contribution of these strategies in reducing aviation emissions while spotlighting the practical, economical, and legislative barriers towards implementation. SAF is the near-term solution for lowering lifecycle carbon emissions compared to conventional jet fuel. Yet, its expansion is hindered by high manufacturing costs, inadequate production facilities, limited feed stock and logistical limitations. This study highlights that even if technology is available, global expansion of SAF requires collaborative investments, long-term purchasing strategies, and inter-regional regulatory support.

Fleet modernization is the other strategy in lowering aviation emissions. Modern aircraft equipped with fuel-efficient engine models, composite material to reduce weight and enhanced aerodynamic designs contribute to lowering emissions. To further improve operational efficiency, AI and digital technologies are implemented. Nevertheless, fleet modernization is costly and beyond affordability for small and medium-sized airlines. Environmental impacts during aircraft manufacturing, disposal and component recycling highlight the importance of circular economy principles in emissions reduction and resource optimization.

This study also evaluates the airlines' behavior on sustainability through R&D, stakeholder collaboration and commercial partnerships. Passengers are increasingly engaging in emission reduction with the influence of voluntary SAF contribution schemes, carbon calculators, and company sustainability reports to the public. Even though these strategies show positive changes in customer travelling decisions, the precise influence on the customer behavior is undetermined, hence needing future research.

The future of the industry is determined by a combination of regulatory provisions, economic incentives and technological advancements. Standard carbon accounting and transparent partnerships are essential in encouraging sustainable technological implementation to the industry. A combined alliance of governments, SAF producers, airlines, R&D institutions, and international regulatory bodies help in overcoming the challenges in implementing these practices.

Further, rather than evaluating best practices and suggesting practical recommendations, this thesis highlights important areas with knowledge gaps as a guidance for future research. Areas such as workforce adjustments, equal accessibility to technology, uniform regulations around the world, efficiency of passenger involvement, standard SAF life cycle monitoring and innovation of new feed stock resources were identified as the important areas requiring further research to assist the future industry.

Overall, the thesis builds up the research by addressing that SAF implementation and fleet modernization are inter-dependent sustainable strategies necessitating coordinated establishment. Research findings illustrate the importance of data transparency, cross-sectoral partnerships and regulatory support in establishing long-term sustainable goals within the industry. As the aviation industry struggles in balancing development and environmental commitment, the research provides guidelines for future research and decision-making.

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