UNIVERSIDADE
LUSÓFONA

Centro Universitário de Lisboa
Escola de Ciências Económicas e das Organizações
Mestrado em Economia

SUSTAINABLE AVIATION FUELS

A PATHWAY TO DECARBONIZATION IN AVIATION – THE CASE STUDY OF SWISS INTERNATIONAL AIRLINES

Dissertação de Mestrado apresentada a provas públicas para a obtenção do grau de mestre em Economia, orientada por Professor Doutor Carlos Capelo e coorientada por Professora Isabel Moura

Sérgio Ricardo dos Santos Bastinho Costa
Mestrado | Economia | 2025

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(Versão Final)

Dissertação de Mestrado defendida em provas públicas na Universidade Lusófona, Centro Universitário de Lisboa no dia 26/09/2025, perante o júri nomeado pelo Despacho de Nomeação nº 455/2025 de 19 de Setembro de 2025, com a seguinte composição:

Presidente: Prof.a Doutora Ana Cristina Freitas Brasão, Professora Associada da Universidade Lusófona – CUL;

Arguente: Prof. Doutor José Carlos Dias Rouco, Professor Associado da Universidade Lusófona – CUL;

Orientador: Prof. Carlos Eduardo Capelo Ramos do Rosário, Professor Auxiliar Convidado da Universidade Lusófona – CUL.

Sérgio Ricardo dos Santos Bastinho Costa
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Environmental challenges, like other difficulties faced by humanity, should not lead to despair, but rather inspire solutions through scientific and economic progress.

Steven Pinker, Enlightenment Now (2018)

Acknowledgement

As I reflect on the journey of writing this thesis, I realize it represents much more than just the end of my Master's studies. It is the culmination of a challenging process of balancing my studies with a demanding full-time professional life. Looking back, I recognize that the true value of this experience lies not in the final outcome, but in the journey itself. Ironically, it is only now, as the process ends, that I feel truly prepared to begin.

I have to start with a big thank you to my master's mentor, Professor Isabel Moura, for the incredible support throughout this process. Your wise words of encouragement and motivation at just the right moments have carried me through this journey. Your professional and academic experience, expertise, and pragmatic insights have helped me structure, simplify, and address complex topics. The challenge you proposed further boosted my motivation and made me engage more deeply with this fascinating subject. I cannot thank you enough for agreeing to be my mentor in this thesis.

To my grandfather, Bernardino Bastinho, whose wisdom continues to inspire me every day. Although he had no formal education, I consider him as the most intelligent person I have ever known, teaching me that true knowledge and culture are not confined to books, but can be acquired by the interaction with others and the world. He has always supported my curiosity and encouraged me to question, explore and learn continuously. With every small achievement I think of him – I like to believe he would be proud of me – this time is no exception. His legacy lives on in everything I do.

I dedicate this thesis to my mother, Maria Fernanda, to whom I owe everything. This journey would not have been possible without her immense support and sacrifice. Her strength and unconditional love have shaped every step of my path. Everything I was, am, and will ever be, I owe to her. For that, and for everything she has done for me, I am forever grateful.

Abstract

Aviation is one of the most difficult industries to decarbonize due to technical and economic constraints. Sustainable Aviation Fuels (SAF) are considered one of the most promising solutions to achieve the goal proposed by ICAO of net-zero carbon emissions by the year 2050. This thesis studied the implementation of SAF by SWISS International Airlines through a qualitative case study approach, based on an interview with a corporate sustainability expert and extensive analysis of corporate and institutional reports.

The study finds that SWISS is following a multi-dimensional approach to integrate SAF into their flight operations, including direct procurement, partnerships with innovative producers, and consumer engagement via voluntary market mechanisms. Despite its environmental benefits, SAF still faces significant economic barriers, especially related to production costs, which are three to five times higher than those of carbon-based jet fuel. Regulations such as CORSIA, EU ETS, and ReFuelEU Aviation, combined with a growing consumer awareness and consequent demand for sustainable travel options, are determinant drivers for SAF adoption.

This work contributes to the academic literature by providing empirical evidence from corporate practice, complementing existing techno-economic analysis. The findings offer practical evidence for students, airline professionals and policymakers, highlighting the importance of globally harmonized regulations and effective incentives. The thesis concludes that SAF implementation is challenging, but possible, and already underway - contributing to a broader transition toward a more sustainable aviation.

Keywords: *Aviation, Case Study, Decarbonization, Reduced Emissions, Sustainable Aviation Fuels (SAF)*

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Abbreviations

Acronym	Full Meaning
ASTM	American Society for Testing and Materials
ATM	Air Traffic Management
CCS	Carbon Capture and Storage
CDM	Clean Development Mechanism
CH ETS	Swiss Emissions Trading System
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
EASA	European Aviation Safety Agency
EEA	European Economic Area
EFB	Electronic Flight Bag
EU ETS	European Union Emissions Trading System
FT Fuels	Fischer-Tropsch Fuels
GDP	Gross Domestic Product
GHG	Greenhouse Gases
H_2	Hydrogen
HEFA	Hydroprocessed Esters and Fatty Acids
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ILUC	Induced Land-Use Change
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
MAC	Marginal Abatement Cost
Mt	Megatonne (= 1,000,000 tonnes)
NDCs	Nationally Determined Contributions
PtL	Power to Liquid
RED I	Renewable Energy Directive I
RED II	Renewable Energy Directive II
RPK	Revenue Passenger Kilometer
SAF	Sustainable Aviation Fuels
SBTi	Science Based Target Initiative
SESAR	Single European Sky ATM Research
StL	Sun to Liquid
UNFCCC	United Nations Framework Convention on Climate Change
WEF	World Economic Forum

1 Introduction

The aviation industry is undergoing a transformative shift due to growing pressure to reduce greenhouse gas emissions. This thesis explores the role of Sustainable Aviation Fuels (SAF) within this context. To understand the current state of aviation decarbonization, it is important to examine the industry's recent evolution and its environmental impact. This chapter provides the background and rationale for the study.

1.1 Aviation global market forecast

Aviation has been one of the industries with highest growth ratio over the past decades. Technological developments, high innovation and market liberalization have reduced costs dramatically allowing for a democratization of air travel. The trend is expected to persist in the next few decades, with projections showing a similar growth rate in the near future. The industry has a substantial impact on the global economy, supporting 87.7 million jobs and generating $3.5 trillion in economic output, equivalent to 4.1% of the global Gross Domestic Product (GDP).

Air transport is vital for the global economy, especially for the transport of high-valued time sensitive good, that account for 35% of the world trade by value but represents less than 1% by volume. Airbus forecast indicates that aviation will likely have a compound annual growth of approximately 3.1% per year until 2050, resulting in a cumulative growth factor of approximately 2.5x. Airbus projects that the total number of in-service aircraft in the world will increase from the actual 23.000 to over 46.000 in the same period. (Airbus, 2024a)

If the forecast is confirmed, aviation is expected to contribute to the transport of about 10.000M of passengers per year by 2050 – more than twice the values of 2019 – while supporting 180M jobs and generating more than $8.8 trillion in economic output. Despite the efficiency improvements and the technological development, this growth implies a substantial increase in the fuel used by the sector. In 2019, commercial aviation used approximately 290 million tonnes (Mt) of jet fuel. By 2050 this number is projected to increase to 520 Mt, driven by several factors such as economic growth, increased living standards, population growth and an increased global connectivity (NLR – Royal Netherlands Aerospace Centre & SEO Amsterdam Economics, 2021).

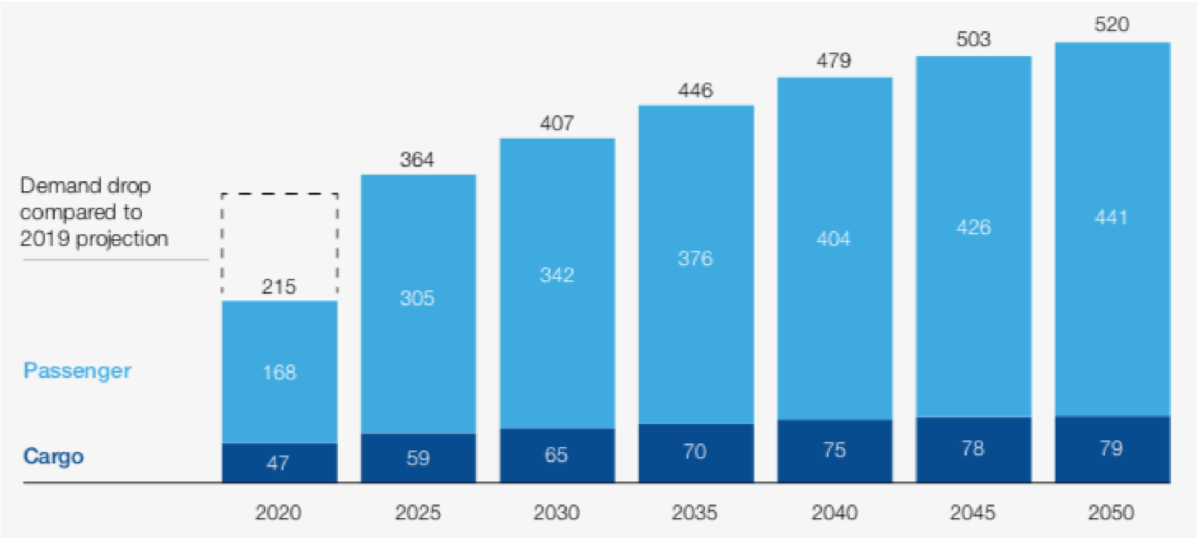

Figure 1: Fuel demand projections (Million Liters). Source: World Economic Forum (2021)

1.2 The problem of carbon emissions

The ongoing development of the aviation sector has made a substantial contribution to the economic growth and human prosperity by facilitating the transport of people, goods, and ideas. But this contribution comes at a cost: carbon emissions. Despite its important role in the global economy, the aviation industry has faced strong critics due to its significant contribution to Greenhouse Gas (GHG) emissions, with the industry being responsible for approximately 2.5% of global anthropogenic CO_2 emissions. (Our World in Data, 2024)

1.3 International agreements

The International Civil Aviation Organization (ICAO), in alignment with the 2015 Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC), has set ambitious targets to reduce CO_2 emissions in aviation and mitigate the environmental impact of the sector. ICAO's primary goals are:

1. A 2% annual improvement in fuel efficiency
2. Carbon-neutral growth from 2020
3. Achievement of net-zero carbon emissions by 2050

ICAO's emissions reduction strategy is based on four key pillars:

Technology developments: The development of innovative and disruptive aircraft and engine technologies is projected to play a substantial contribution toward the objective of achieving net-zero carbon emissions by 2050.

Operations and infrastructure improvements: Improvements in infrastructure and airlines operational procedures are expected to enhance operational efficiency, thereby contributing to fuel efficiency.

Sustainable aviation fuels (SAF): Derived from non-fossil sources, including biofuels and synthetic fuels, SAF have the potential to reduce life-cycle greenhouse gas (GHG) emissions by up to 80%. ICAO projects that SAF will play a critical role in decarbonizing aviation, making the largest contribution to the total emissions reduction required to meet the 2050 carbon-neutral goal. Although new power sources, such as electrification and hydrogen, are emerging, they are classified as aircraft technologies for the scope of this study.

Market-based measures: Since not all emissions can be eliminated through in-sector reductions alone, out-of-sector carbon reduction mechanisms provide a necessary pathway to address residual emissions. These mechanisms enable airlines to invest in projects that mitigate CO_2 emissions elsewhere.

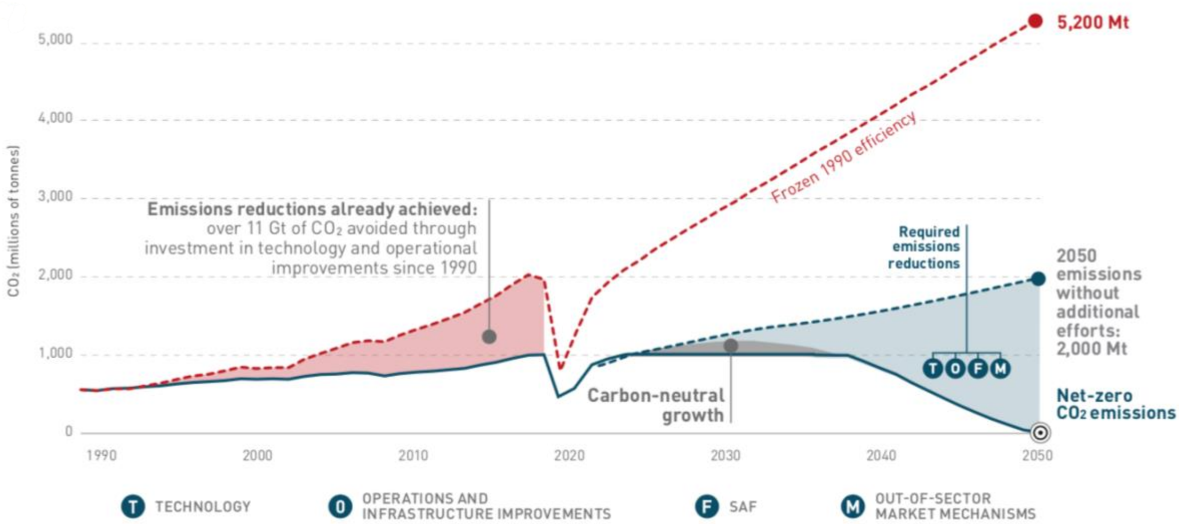

Figure 2: The four key pillars identified by ICAO to achieve Net-zero CO_2 emissions. Source: WAYPOINT 2050 (2021)

The figure above represents the predicted CO2 emissions, comparing a scenario of no additional efforts with a scenario where technology, operations and infrastructures, SAF, and market-based mechanisms are used to achieve the three ambitious goals set by ICAO.

These measures will not only contribute to achieving the three long-term goals described earlier but also aligns with the United Nations Sustainable Development Goals (SDGs), promoting sustainable global, social, and economic development. (UN, 2024)

1.4 Sustainable Aviation Fuels

Sustainable Aviation Fuels (SAFs) are alternative fuels derived from renewable sources that offer a significantly lower carbon footprint compared to conventional fossil jet fuels. Their compatibility with existing aircraft and infrastructure makes them the viable near-term solution to decarbonize aviation.

Even with all the improvements in aircraft technologies, large commercial aircraft have no alternatives to liquid fuels in the near or mid-term future. After many years of research and development, turbofan engines have become extremely reliable and economically efficient, with a huge power-to-weight ratio, they allow for an excellent range due to the high energy density of liquid fuels. In this regard emerges the concept of 'drop-in' SAFs as the most promising near-term solution. Drop-in ready means that these fuels can use the same fuel distribution infrastructure, aircraft, and aircraft engines currently in use, without modifications, offering immediate CO_2 reductions. (ICAO, 2018)

The International Air Transport Association (IATA) monitored the Sustainable Aviation Fuel (SAF) production over the recent years and projects a steady increase for the future, but still below the optimal level. In 2022, SAF production was about 0.25 Million tonnes (Mt), in 2023 this figure doubled to 0.5 Mt and further increased to approximately 1.5 Mt in 2024. Looking forward, total SAF production is expected to reach 2.1 Mt in 2025, representing only about 0.7% of the global jet fuel production, by volume. Despite the increase in production, SAF still accounts for only a small fraction of the aviation sector's fuel demand. (IATA, 2024b)

1.5 Research Purpose

There is a scientific consensus that Sustainable Aviation Fuels (SAF) are a key component for a more sustainable aviation, as supported by the existing literature and the scientific knowledge.

Our study addresses the topic of SAFs by defining these fuels, presenting the current pathways, its environmental benefits, but also identifying the economic and technical challenges of adopting SAF, and analyze the role of airlines in the implementation of SAF from an economic and environmental perspective. The literature review revealed a scarce knowledge on the implementation of SAF by airlines, despite several studies devoted to SAF production and distribution methods or even cost predictions. This work addresses this gap by giving insights into the key drivers, the main challenges, but also opportunities encountered during the adoption of SAF, by looking into the case of SWISS International Airlines.

The theoretical goal of this thesis is to investigate the current state of the art of Sustainable Aviation Fuels (SAF) as a potential solution to decarbonize aviation and contribute to achieve the ultimate long-term goal of achieving net-zero carbon emissions by the year of 2050.

The practical goal of this thesis is to explore the implementation of SAF by SWISS International Airlines in the context of a case study, identifying the drivers, the challenges, the opportunities and the risks involved.

1.6 Research Questions

This work aims to answer the following research questions:

- Can Sustainable Aviation Fuels (SAF) support the aviation industry's goal of net-zero carbon emissions by 2050 while contributing to global economic development and maintaining airlines economic viability?
- Why and how is SWISS International Airlines implementing SAF in its operations?

1.7 Scope and Structure

The thesis is structured into eleven chapters, organized as described below:

In the first chapter, the research topic is introduced looking into the background and rationale for the study. The research purpose and questions are presented, followed by the scope of the study.

The second chapter presents the literature review, which serves as the theoretical foundation of this study.

In chapters three to six, we expand the theoretical foundation of the study. The third chapter is dedicated to examine how aircraft and engine technologic development can contribute to achieve the so desired decarbonization in the aviation industry. The fourth chapter looks into how operations and infrastructures can contribute to the same objective. The fifth chapter focuses on Sustainable Aviation Fuels (SAF) as the main mean of achieving carbon neutrality. Finally, the sixth chapter delves into market-based mechanisms as a mean of providing out-of-sector offsets for the unavoidable carbon emissions.

In the seventh chapter, the research methodology applied in this thesis is described, and the iterative process of data collection and analysis is explained in detail.

In the eighth chapter, we present the main findings derived from the data collected and analyzed.

In the nineth chapter, the discussion addresses the initial research questions using the results derived from data analyzed.

The chapter ten summarizes all the findings and presents the author's final thoughts, and chapter eleven presents the main limitations of the study and suggest recommendations for potential future research.

Finally, the chapter eleven presents the most relevant limitations of the research and suggests possible directions for future research.

2 Literature Review

Building on the background introduced in Chapter 1, this chapter reviews the academic and institutional literature on the four ICAO pillars, with special focus on SAF as a decarbonization key element.

2.1 The Four Pillars of Aviation Decarbonization

In response to the commitments defined in the Paris Agreement, ICAO and IATA developed a four-pillar strategy to achieve net-zero carbon emissions by 2050. These pillars are: (I) aircraft and engine technologies, (II) operational and infrastructure improvements, (III) sustainable aviation fuels, and (IV) market-based measures. This framework serves as the conceptual foundation of most institutional and academic work on aviation decarbonization (ATAG, 2021a; ICAO, 2022b).

Most of the academic literature has adopted and expanded this framework through techno-economic, scenario, and policy analysis (Dray et al., 2018). These studies offer insights into the relative effectiveness and cost-efficiency of each pillar, emphasizing the need for an integrated approach combining both in-sector and out-of-sector measures.

This approach supports the economic principle of cost-effective abatement, an idea connected to the concept of economic efficiency in emissions reductions, where actions that achieve the greatest emission reductions at the lowest cost should be prioritized, regardless of the sector (Stern, 2006).

2.2 Aircraft Technology and Innovation

Historically, aviation has always been a driver for technological improvements, with advancements in aircraft and engine design contributing to a remarkable fuel efficiency.
Literature calls attention to innovations such as geared turbofan engines, high-bypass ratio engines, blended body-wing airplanes, the use of composite materials or metal addictive manufacturing as critical enablers of fuel savings (Blakey-Milner et al., 2021; GE Aerospace,

2024). Research shows that evolutionary technological improvements can yield 20-25% fuel efficiency per each new aircraft generation (ATAG, 2021b).

From a theoretical point of view, these improvements are aligned with the principle of induced innovation, where technological evolution is driven by environmental regulations and energy price (W. D. Nordhaus, 2010). However, the pace of fleet renewal is slow, due to the long lifecycle of aircraft (25–30 years), which creates a problem where these innovations alone are not sufficient, to meet long-term emissions goals (Airbus, 2024a). Another factor contributing to this is the capital-intensive nature of the sector, combined with the complex certification process required by aviation safety authorities, which significantly delay the rapid deployment of revolutionary designs, like blended wing body configurations or hydrogen-powered propulsion (Peeters et al., 2016).

Current aircraft technologies and infrastructure are dependent on fossil-based fuels. This concept, known as 'carbon lock-in,' can only be overcome through coordinated policy and investment signals that support the transition to next-generation technologies (Unruh, 2000). In the mid-term, solutions that include actual technologies and infrastructures are essential to achieve the industry goals.

2.3 Operational and Infrastructure Improvements

Operational measures like single-engine taxiing, electronic flight bags, engine washing or optimized flight paths are practices contributing to incremental reductions in fuel consumption and emissions (ANA, 2024; Lufthansa Technik, 2024). Infrastructure improvements, such as modernization of air traffic management - SESAR in Europe and NextGen in the U.S. - or airport improvements can also offer emission reductions through enhanced efficiency (FAA, 2025; SESAR, 2025a).

Economic literature frames these improvements in terms of marginal abatement cost (MAC) curves. Studies show that many operational measures may fall within the negative-cost segment of the MAC curve, that means that those measures can reduce emissions while lowering operational costs (Stern, 2006). However, their cumulative potential is limited, and rebound effects - such as increased traffic enabled by efficiency gains - may offset part of the savings.

Some authors suggest that the sector may be approaching 'efficiency saturation', the point at which further operational improvements yield diminishing returns (Dray et al., 2018; Graver et al., 2020). This underscores the need to complement such measures with deeper systemic changes, including demand-side interventions and the incorporation of Sustainable Aviation Fuels (SAF).

From a macroeconomic perspective, total emissions are a function of three key drivers: population growth, rising GDP per capita, and the carbon intensity of GDP. While the first two are exogenous to the sector, carbon intensity is the only variable that can be controlled via policy and technological change, such as the adoption of SAF (W. Nordhaus, 2013).[1]

While progress in fuel efficiency and operations continues, the current rate of improvement remains insufficient to bend down the emissions curve, particularly due to the strong growth in air travel demand.

2.4 Sustainable Aviation Fuels (SAF)

Sustainable Aviation Fuels (SAF) are widely seen as the most promising near-term solution to reduce aviation's carbon footprint, with the potential to cut up to 80% greenhouse gas emissions when compared to fossil fuels (IATA, 2024). Typically, SAFs are classified into biofuels and synthetic fuels and can be produced via various ASTM-approved pathways, such as HEFA, Fischer-Tropsch, and Alcohol-to-Jet (ASTM, 2022).

We found academic literature exploring the technical feasibility, economic viability and environmental benefits of SAF (Detsios et al., 2023; Pavlenko et al., 2019). These studies emphasize the importance of ASTM certification, drop-in compatibility, and the potential for lifecycle carbon reductions, particularly when using waste-derived feedstocks (ATAG, 2021b). However, the broad adoption of SAF is slow down by its high costs, limited feedstock availability, small economies of scale and regulatory uncertainty.

[1] This decomposition is consistent with the Kaya identity framework commonly used in environmental economics.

Among the available pathways, HEFA is currently the most cost-effective pathway, while Power-to-Liquid (PtL) offers the highest long-term potential due to scalability and near-zero emissions - provided that renewable electricity is used (Batteiger et al., 2022a). Economic studies using levelized cost models suggest that PtL SAF can only become cost-competitive with fossil fuels if carbon prices exceed \$300/ton CO_2 or if production costs fall below €2/litre through economies of scale. To achieve cost parity, the literature reinforces the need for policy instruments such as subsidies, tax incentives, and blending mandates (Pavlenko et al., 2019).

There is broad consensus that biofuels alone cannot meet long-term aviation fuel demand. In contrast, synthetic fuels are considered more scalable, provided the use of renewable electricity and carbon capture technologies. Scientists warn for the risk of technological lock-in, where early investments may favor mature but less sustainable options like HEFA, delaying the development of more advanced pathways (Schmidt et al., 2018).

2.5 Market-Based Mechanisms

Despite all the emissions reduction achieved through aircraft technology, operational improvements, and SAF deployment, a part of aviation emissions remains unavoidable in the near term. Market-based mechanisms are a complementary strategy to in-sector decarbonization efforts. Instruments like EU Emissions Trading System (EU ETS) and ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), allow airlines to offset the residual emissions by buying and trading carbon credits (EU, 2014; ICAO, 2019).

The main economic theory behind these mechanisms is the principle of the internalization of negative externalities through Pigouvian prices. This could be done through direct carbon taxes, but, in practice, especially in the aviation sector, these taxes are difficult to implement and politically sensitive (Aldy & Stavins, 2011). As result, alternatives like emissions trading systems and carbon offsetting have been introduced. These tools offer more flexibility and can also deliver emissions reductions more efficiently, as they focus on reducing emissions in industries where the marginal abatement costs (MAC) are lower, aligning environmental objectives and economic efficiency.

Comparative studies were dedicated to analyze the important differences between these systems. The EU ETS operates on a cap-and-trade principle, where emissions are limited by a cap and the allowances are traded. The number of allowances is progressively reduced, tightening the market and, while they create a price sign that drives down emissions. Their true effectiveness is dependent on allowance scarcity, the quality of the offset projects and the integration with other mechanisms (Dechezleprêtre et al., 2023). CORSIA, for example, has been criticized for its weak enforcement nature, reliance on questionable offsets, and insufficient alignment with the Paris Agreement goals (Newell & Pizer, 2000).

Another critical issue is the integrity and transparency of offset markets. Problems like weak governance, double counting, or non-additionality in offset projects can subvert the climate benefits of these mechanisms, presenting a reputational risk for airlines that might affect investor confidence in voluntary and compliance-based offsetting markets.

Some literature examines how these mechanisms interact with innovation. While a rising carbon price provides a broad incentive to decarbonize, it may not be sufficient to drive the high-risk R&D investments required for technologies like SAF, Direct Air Capture, or green hydrogen. Authors such as Acemoglu et al. (2009) emphasize the need for complementary innovation policies - such as targeted subsidies, public-private partnerships, and technology mandates - to change the economic panorama toward low-carbon pathways without compromising long-term growth.

Market-based mechanisms are a necessary bridge in aviation's decarbonization strategy, their design, enforcement, and integration with other policies significantly determine their effectiveness. In the context of SAF, carbon pricing can help to close the cost gap with fossil jet fuels, particularly if prices rise above certain thresholds (e.g. \$300/ton CO_2 for PtL fuels), but must be complemented by broader industrial and innovation policy support to unlock their full potential (Batteiger et al., 2022b).

The four-pillar framework has been examined in detail across the previous sections. The following table provides a summary of their relative potential, economic characteristics, and key limitations, synthesizing the academic and institutional literature reviewed.

Table 1: Summary of ICAO's four pillars: Emission Reduction Potential, Economic Considerations and Key Limitations. Source: Own elaboration (2025)

Pillar	Emission Reduction Potential	Economic Considerations	Key Limitations
1.Aircraft Technology	Medium/High (20-25% per gen)	Capital-intensive Long investment cycles Aligned with induced innovation	Slow fleet renewal High R&D costs Carbon lock-in
2. Operations and Infrastructures	Low/Medium	Often cost-saving (negative MAC) Quick to implement	Efficiency saturation Rebound effect
3. Sustainable Aviation Fuel (SAF)	High (up to 80% GHG reduction)	High costs / Subsides required PtL more scalable Dependent on carbon pricing	Cost gap Feedstock scarcity Infrastructures required
4.Market-based Mechanisms	Medium (complements to other pillars)	Cost-effective allocation Pigouvian pricing Flexibility with offsets	Offset quality issues Political constraints CORSIA weak enforcement

2.6 Research Gap

A substantial body of literature exists on Sustainable Aviation Fuels, including their production pathways, cost projections, environmental benefit, and regulatory frameworks. However, it remains a notable lack of knowledge on how the major airlines are implementing SAF in practice. Most of the studies are dedicated to understand SAF at a techno-economic level or on an environmental perspective. However, there is a noticeable gap in qualitative insights into corporate-level dynamics, including decision-making processes, market forces, and the barriers shaping SAF adoption at the airline level.

To address this gap, the present thesis investigates the SAF integration strategy of SWISS International Airlines using a qualitative case study approach, offering a microeconomic and qualitative perspective that complements existing quantitative analyses.

2.7 Summary

This literature review has synthesized key academic and institutional papers on aviation decarbonization strategies. SAF has emerged as the most promising near-term solution, although its adoption remains constrained by economic and logistical barriers. Operational and technological innovations are expected to contribute marginally while market-based mechanisms offer a necessary bridge. The literature provides the economic theory, including externality pricing, marginal abatement costs, induced innovation, and policy instruments to evaluate these pathways.

Little is known about the implementation of SAF on an airline level, highlighting the relevance of this thesis in providing a grounded, real-world analysis, that makes a contribution on both academic theory and corporate practice.

3 First Pillar - Aircraft Technology

Although its relatively low contribution of about 2.5% to total carbon emissions, aviation is widely seen as one of the most challenging sectors to decarbonize, due to technological and economic factors. From a technological point of view, there is currently no viable alternative to large airplanes equipped with large high-bypass turbofan engines that rely on liquid fuels with high energy density, particularly for long-distance flights. From an economic perspective, alternatives must consider the financial viability of the airlines, which typically operate on tight profit margins.

Another important factor is that aircraft are extremely valuable assets that take a long time to develop and build and many years to pay back the initial investment. Typically, aircraft remain in service for a period of 30+ years (Airbus, 2024c) meaning that fleets renovation tends to be slow. This means that many aircraft that will be in operation by 2050 are being manufactured 'today', therefore short-term and medium-term solutions must include in-use airplanes. Building an airplane is a complex process that takes a long time from start to certification. The process consists of designing, building, testing and a long certification process, where it has to pass rigorous tests to prove the highest safety standards. The entire process of designing an airplane takes approximately 10 years, from its initial drawing to the moment the aircraft enters into service for operation. For instance, the state-of-the-art Airbus A350 design project was initiated in 2004 and received its type certification from the European Aviation Safety Agency (EASA) in September 2014 (EASA, 2014).

Aviation is a highly competitive industry and has always had huge incentives for innovation. By the nature of the business, weight reduction, technological innovation or enhanced efficiency have been rewarded with profit margins but also with sustainability gains. The rate of technological development in the aviation industry is well above that of other sectors, with average annual improvement of 2%. Each new generation of aircraft entering into service provide an immediate 20-25% fuel and CO_2 reduction when compared with the previous generation (ATAG, 2021b).

On its report WAYPOINT 2050 the Air Transport Action Group (ATAG) forecast that investments and gains in new technologies can have a contribution between 12% to 34% of total emissions reduction, depending on the level of investment of various stakeholders in new evolutionary and revolutionary technologies. For that to happen, the aviation sector, government and policymakers, research institutions, energy industry, finance institutions, and other stakeholders must work in collaboration (ATAG, 2021b).

3.1 Evolutionary Technologies

In the short term, evolutionary technologies will have an important contribution to reduce fuel used and carbon emissions on the next generation of traditional aircraft. This means the incorporation of technology that is currently being developed into existing aircraft types as they come out of production line over the coming years, or even retrofitted into in-service aircraft. Some of the technologies with greater potential are described below:

Metal additive manufacturing: Additive manufacturing (AM), well known as 3D printing, has emerged as an important breakthrough in the aeronautical industry, revolutionizing the design and production of aeronautical components. This technology is able to manufacture components layer-by-layer based on digital models, open the possibility to create complex geometries that were not possible with traditional methods. AM enables significant weight reduction, essential in the aviation industry, combined with more intricate designs. This technology also offers quick prototyping capabilities, which results in reduced development time and costs. AM also gives the possibility to produce components on demand, reducing inventory stock with the consequent cost reduction, making it an essential technology for the progress of aviation (Blakey-Milner et al., 2021).

Geared turbofan engines: GTF engines have a gearbox incorporated between the fan and the compressor, allowing each of those components to rotate at its optimal speed. On previous generations of turbofan engines, the core speed was limited by the speed of the fan, because at higher compressor speeds the fan tips would reach supersonic speeds with consequent shock waves. This innovative solution significantly enhances the propulsive attributes of the engine, contributing to improved efficiency and reduced emissions. This new generation of engines are certified as an option for A320neo, providing remarkable fuel savings and less range limitations (Pratt & Whitney, 2024).

High-pressure ratio engines: High pressure ratio engines offer significant advantages in terms of performance and specific fuel consumption (the amount of fuel required to produce a unit of thrust). The compressor provides higher pressures prior to combustion, allowing the engines to achieve a greater thermal efficiency, increased power production, and reduced specific fuel consumption and emissions. The GE9X was developed by General Electric specifically to be used with the new Boeing B777X. This innovative turbofan engine has a pressure ratio of 27:1 and uses new materials like Ceramic Matrix Composites (CMC) or Additive Manufacturing (AM) materials. The GE9X is at least 10% more fuel efficient and presents even lower emissions than the previous generation of turbofan engines from the manufacturer (GE Aerospace, 2024).

UltraFan engines: Rolls-Royce is currently developing a new turbofan engine for commercial aviation. In propulsion systems, it is more energy-efficient to accelerate a larger mass of air at a lower velocity than to accelerate a smaller mass at a higher velocity, this design achieve greater propulsive efficiency by moving a larger volume of air with relatively lower exhaust speeds. This principle demonstrates the benefits of an increased fan diameter. The UltraFan engine from Rolls-Royce features an ultra large fan with 140 inches (3.5m) in diameter, making it the largest engine in the world. With the advanced technology and materials used, this engine is expected to have 25% better performance and efficiency when compared with the previous models. The engine will also be certified to operate with 100% Sustainable Aviation Fuels (Rolls Royce, 2022).

Composite structures: Each new generation of aircraft are manufactured with the application of lightweight composite materials, such as carbon fiber. This not only has evident effects in terms of weight saving, and the consequent fuel and emissions reductions, but also has the advantage of being less susceptible to fatigue failures and corrosion. There is potential to apply these materials to even more parts of the aircraft, in the future.

Wingtip devices: Winglets are devices that are being introduced in the new models or retrofitted into in-operation aircraft. The aerodynamic devices, tilted upwards at the wingtips, decrease the vortex generated at the wingtip, reducing induced drag, which has delivered a 3-5% reduction of fuel used (ABBB, 2024).

AeroShark: Biomimicry is an example of a new approach to aircraft innovation. Inspired by shark skin, Lufthansa Technik and BASF developed a film with small grooves to be added to the aircraft surface. SWISS International Airlines was the first company in the world to implement the innovative technology, by applying 950 m2 of AeroShark riblet film on its 12 Boeing B777 fleet. The calculation indicates 1.1% fuel saving. This reduction in fuel consumption was estimated to be 4800 tonnes per year, with the corresponding 15200 tonnes of CO_2 avoided annually (SWISS, 2023a).

Active load alleviation: Introducing this function, provided by fly-by-wire flight controls, enables an active load reduction during maneuvers, turbulence and gust, allowing for a less massive wing structure, thereby reducing the overhaul weight and, consequently, emissions.

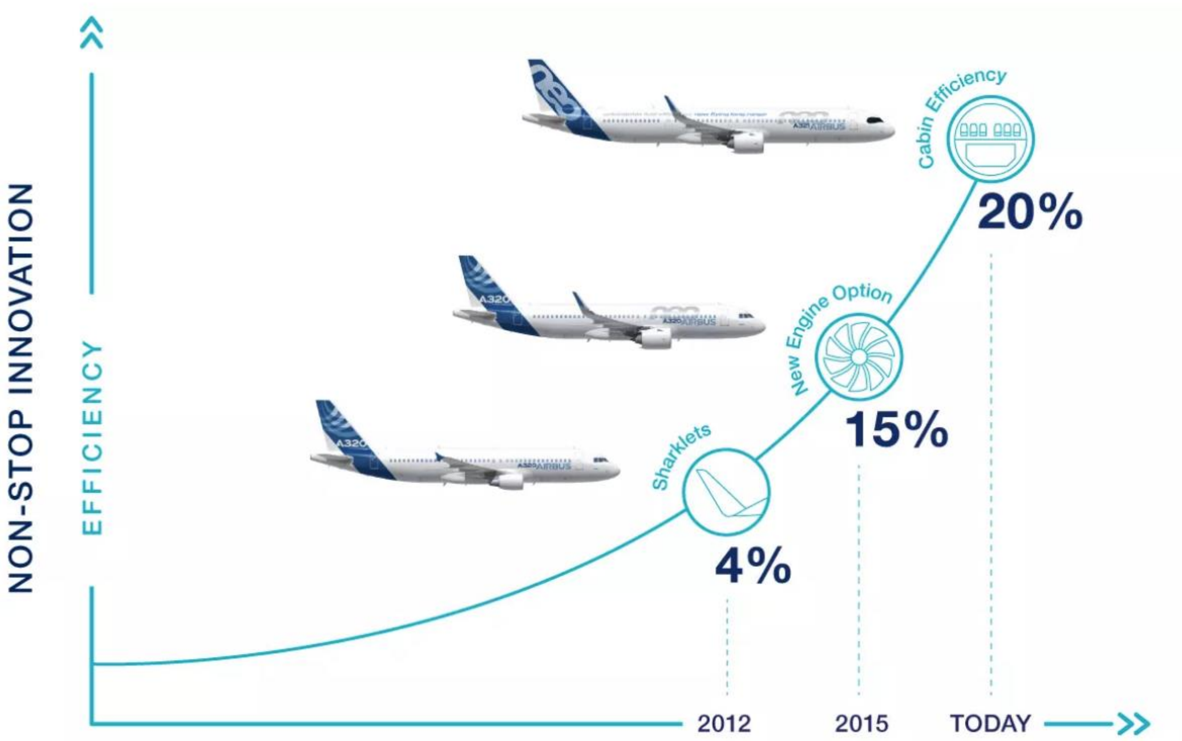

Figure 3: Airbus evolutionary technologies. Source: Airbus (2024)

The figure above illustrates the continuous improvements in efficiency within the Airbus A320NEO family through evolutionary technological innovations. With the introduction of innovative solution to the new aircrafts coming out of the production line, such as large sharklets, NEO engines and innovative airspace cabin design, Airbus achieved a cumulative efficiency gain of 20% when comparing with the previous model. These new fuel-efficient aircraft modifications allowed for a better environmental performance, including reduction in NOx and CO_2 emissions.

3.2 Revolutionary Technologies

In the long term, revolutionary aircraft and engine technologies will have a significant contribution for the future of a more sustainable aviation industry. More specifically, these innovations are expected to contribute with efficiency gains to a significant reduction in the specific fuel consumption and, consequently, emissions.

3.2.1 Revolution in Aircraft Design

On the aircraft side, the traditional aircraft design is the so-called ‘tube and wing’. Although it has proven to be an efficient and reliable design, may not be the most efficient and other alternatives are being developed for the future, such as:

Canard: Conventional commercial aircraft designs feature a horizontal stabilizer at the tail of the airplane. By being located behind the main wing, horizontal stabilizers are designed as ‘inverted airfoils’ that have a negative impact for lift and drag. Placing a canard forward of the main wing, contributes to lift and reduces overall drag, but this configuration incurs at a cost of some stability issues that arise. However, these issues can nowadays be solved by modern fly-by-wire flight control systems.

Truss-braced wings: NASA and Boeing are working on the concept design of a truss-braced high aspect-ratio wing. The research goal is to develop a wing with high wingspan without adding structural weight, which results in a high-performance wing with very low induced drag and, consequently, lower engine thrust requirements. This design could be associated with revolutionary propulsion systems to achieve even better performances (NASA, 2023).

Box wing: Studies have shown that this configuration ensures a minimum level of induced drag and significantly reduces fuel consumption, when compared to a conventional aircraft design, for any given wingspan and weight. This design connects the tips of the two offset horizontal wings and aims to increase the passenger capacity and simultaneously reducing total fuel consumption and using the existing airport infrastructures. This design is intended to be used together with future propulsion technologies (Tasca et al., 2021).

Blended wing-body design: This innovative aircraft design developed by Airbus presents a fixed wing aircraft without a clear differentiation between the wing and the fuselage, like a delta-wing. With this configuration, a wide airfoil-shaped body, the entire airplane is engineered to create lift and presents a much better lift-to-drag ratio compared with a conventional aircraft. According the tests conducted, significant fuel savings are anticipated. The tests have demonstrated approximately 20% less fuels consumption than a comparable single aisle model equipped with the same engines (Airbus, 2020c).

Figure 4: Airbus blended-wing revolutionary aircraft concept. Source: Airbus (2020)

Airbus, the manufacturer, its committed to explore innovative design concepts that can contribute to improve efficiency and significantly reduce CO_2 emissions. Two such examples are the Albatross and eXtra performance wings, concepts that are being studied and developed for an eventual future aircraft concept developed by the European manufacturer (Airbus, 2023).

3.2.2 Revolution in Propulsion System

Nowadays commercial aircraft use two main types of engines: turbofans and turboprops. These engines can operate on either fossil fuels or a mix of fossil fuels with up to 50% Sustainable Aviation Fuels. However, new alternatives are being developed both in terms of engine concepts and energy sources. This sub-chapter presents some of the future developments.

Electric propulsion: On this configuration, electric motors are used to power conventional large propellers or small fan units. Electric power is stored in large batteries, with the clear disadvantage of being much less energy-dense than liquid fuels. During operation the CO_2 emissions of electric aircraft are near zero but, the lifecycle total emissions are highly dependent on the primary energy source used to generate electricity. If renewable energy sources are used, emissions can be minimal. This technology is promising for small regional aircraft but not for large intercontinental aircraft.

Hybrid-electric propulsion: The hybrid-electric concept integrates the benefits of both combustion and electric engines. The combination of these propulsion systems provides the maximum thrust during takeoff. During cruise flight or descent, the combustion engine can be throttled back, thereby reducing the onboard weight. This propulsion technology can be combined with the already mentioned revolutionary aircraft designs.

Hydrogen-powered engines: Hydrogen is a clean-burning fuel that only releases water vapor (H2O) into the atmosphere and it can be burned directly for propulsion in conventional engines or as an electrical power source in fuel cells. There are several obstacles to its use in aviation, such as a low global availability of green hydrogen or lack of suitable supply infrastructures. Another important factor is that despite it has the highest energy per mass of any fuel at 120 MJ/kgH_2, hydrogen has a very low volumetric energy-density of 8 MJ/L for liquid hydrogen where jet fuel has 34.7MJ/L (IEA, 2023).

Open rotors: The propulsive efficiency reflects the proportion of the mechanical energy that is actually used to propel the aircraft and its maximized when the engine exhaust gas velocity is closest possible to the aircraft speed. In propulsion systems, it is more energy-efficient to accelerate a larger mass of air at a lower velocity than to accelerate a smaller mass at a higher velocity, which can be achieved by increasing the fan blades diameter. With this concept in mind, CFM is currently developing an open-rotor engine expected to present specific fuel consumption and CO_2 emissions 20% lower than the actual state-of-the-art engines with nacelle. CFM RISE will as well ensure compatibility with alternative energy sources like Sustainable Aviation Fuels (SAF) and hydrogen providing even further sustainability benefits (CFM, 2024).

Figure 5: CFM RISE revolutionary open rotor propulsion concept. Source: CFM (2024)

It is important to note that while alternative propulsion systems, such as electric or hydrogen-powered engines, may be an alternative to domestic short-haul flights on smaller aircraft, they are not expected to replace liquid fuels as primary energy source for aviation, in the future. This is due to some significant technical constraints, including weight limitations, difficulties in hydrogen storage and transport, and hydrogen's lower volumetric energy density compared to conventional liquid fuels.

4 Second Pillar - Operations and Infrastructures

Improvements in operations and infrastructure have been identified by ICAO and IATA as a fundamental pillar to contribute to achieve net-zero carbon emissions by 2050 with the potential to significantly enhance fuel efficiency, and so reducing direct, indirect, and induced emissions. ICAO forecast that investments in Operations and Infrastructures can have a cumulative contribution between 7 to 10% of the total emission reductions needed to achieve carbon neutrality. But the two organizations advice for the risk of the gains made in those fields being offset by the possible degradation resulting from airspace congestion caused by significant traffic increase (ICAO, 2022b).

As an example, the following diagram shows some of the best practices regarding flight operations implemented by one of the most successful Japanese airlines, All Nippon Airways (ANA, 2024).

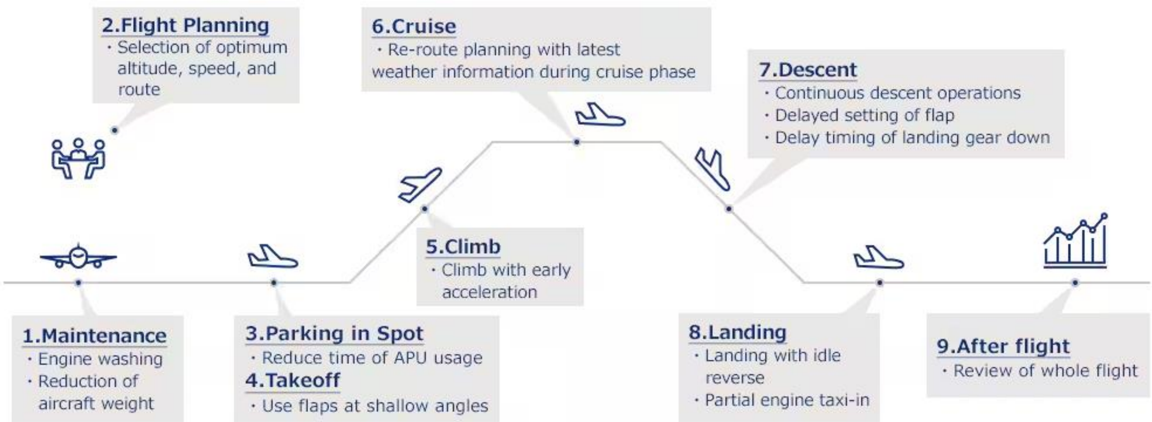

Figure 6: Improved in flight operations. Source: ANA (2024)

4.1 Operational Improvements

There is a wide range of operational improvements, with the potential to reduce emissions, that might be applied by the airliners in the future. These measures may include the following:

Engine wash: Over time, engine performance is degraded by factors like erosion, wear and contamination from the elements. This is monitored by the value of Exhaust Gas Temperature (EGT) margin. EGT margin is the difference between the engine's EGT during a full-rated takeoff at reference conditions and the EGT limit set by the manufacturer. Lower EGT margins is an indication that the engine needs to burn more fuel and reach a higher EGT to produce the same level of thrust. Engine Condition Monitoring departments tracks engine degradation and schedule engine washes that increase the EGT margin, decreasing fuel consumption and, subsequently, decrease emissions. Lufthansa Technik data shows that engine washes contribute to increasing EGT margin, reduction in fuel flow up to 1.5% and increased average on-wing time of the respective engine (Lufthansa Technik, 2024).

Electronic Flight Bags (EFBs): Airlines are replacing traditional paper-based manuals, documentation and logbooks with electronic flight bags, with the clear advantage of reducing weight and providing flight crews with real-time data to optimize flight operations.

Reviewing flight paths during flight using the latest weather information: Modern communicating systems are allowing airlines to check real-time weather information again after takeoff and change the flight routes accordingly. This Dynamic Airborne Reroute Procedure (DARP) allows for more optimal fuel planning and flight routes, contributing to fuel savings and reducing CO_2 emissions (ANA, 2024).

Last-Minute Fuel and Water Uplift: Fuel and potable water uplifts are adjusted last minute with the real-time information to prevent carrying unnecessary weight with evident benefits.

Wake energy retrieval: Airbus is using biomimicry by emulating the V-shaped flight pattern of migrating geese using wake energy retrieval. The fello'fly project employs this principle, enabling the following aircraft to benefit from the upward wake of air created by the leading aircraft, resulting in a reduced engine thrust and fuel consumption during commercial operations. This innovative biomimetic solution has the potential to reduce CO_2 emissions by at least 5% (Airbus, 2024b).

Single-Engine Taxiing: Specially in congested airports aircraft have long ground time taxiing between stands and runways, with a significant impact on fuel consumption. By adopting single engine taxiing operators can significantly reduce fuel consumption during ground operations.

4.2 Infrastructure Improvements

From an infrastructure perspective, there are several measures that can be adopted by operators, airports or authorities with huge potential to reduce CO_2 emissions, such as:

Modernization of Air Traffic Management systems: SESAR is a European Union initiative designed to modernize and harmonize Air Traffic Management (ATM) in Europe. It is key component of the Single European Sky (SES) and its main goals are to enhance the efficiency, capacity and safety of the European airspace. The SESAR initiative requires cooperation among airlines, airports and air navigation service providers (SESAR, 2025b). With the same goals for the United states of America airspace, the Federal Aviation Administration (FAA) has launched an initiative named NextGen, which objective is to modernize the National Airspace System (NAS) by transforming the current Air Traffic Control (ATC) system into a more efficient, automated, and integrated system using advanced technologies (FAA, 2025).

Reducing Auxiliary Power Unit (APU) usage: Aircraft are equipped with a small engine located in the tail compartment, called APU. On ground, this unit is responsible to provide electrical power for ground operations and pneumatic pressure used for air conditioning or for main engines start. APU operation burns significative amounts of fuel and emits CO_2. To save fuel, airlines must reduce its usage time by using Ground Power Units (GPUs) to supply electrical power or air conditioning to the aircraft while on ground. Airports are also reducing the use of diesel GPUs by replacing them by fixed energy systems with evident ecological benefits. The Table below shows a comparison of the CO_2 emissions per hour of operation for APUs, GPUs and the fixed energy system (Zurich Airport, 2018).

Table 2: Specific CO_2-emissions (kg/h) of APU, GPU and fixed electricity. Source: Zurich Airport (2018)

	APU kg CO_2/h	Diesel GPU kg CO_2/h	400 Hz kg CO_2/h[1]
Shorthaul Aircraft	337	19.1	0.7
Longhaul Aircraft	758	38.2	1.2

[1]Emissions from Swiss electricity production

Continuous Descent Approach: CDA is a navigation method in which an aircraft descends continuously from the Top of Descent (TOD) until the final approach point. This method allows for the aircraft to spend more time in cruise, where the flight is more efficient, shortens the total flight distance and reduces the engine power variations during descent with evident positive consequences on fuel consumption, CO_2 emissions and noise (EUROCONTROL, 2024).

4D Trajectory-based Operations: 4D-TBO is an advanced concept to reduce air traffic management (ATM) inaccuracy based on the real-time transmission of four-dimensional trajectory data. The transmission of latitude, longitude, altitude and time enhances the efficiency, predictability, and safety of air traffic by allowing a more precise control and coordination of the aircraft routes (Airbus, 2020a).

5 Third Pillar – Sustainable Aviation Fuels

In this chapter we define Sustainable Aviation Fuels (SAFs), identified by ICAO and IATA as the main pillar to decarbonize aviation. We also look into its characteristics and the different pathways available at the moment for SAF production. The chapter also provides a techno-economic analysis of these fuels and makes an environmental assessment of each pathway. At a later stage we explore the regulations affecting SAF deployment and the key demand drivers and the obstacles that must be overcome in order to do so.

5.1 Introduction to Sustainable Aviation Fuels

Sustainable Aviation Fuel (SAF) are a non-fossil-based fuels that serves as a direct replacement for conventional jet fuel offering considerable reduction in carbon emissions throughout its lifecycle. SAFs can be produced from renewable resources such as waste oils, agricultural residues, municipal solid waste, algae or other sustainable feedstocks. On a chemical level it is similar to traditional jet fuel, allowing it to be used in existing aircraft and infrastructure without any modifications. Among the most relevant environmental attributes of SAF is its potential to reduce greenhouse gas (GHG) emissions by up to 80% with the possibility of achieving even higher reductions as production methods continue to advance (Airbus, 2024d).

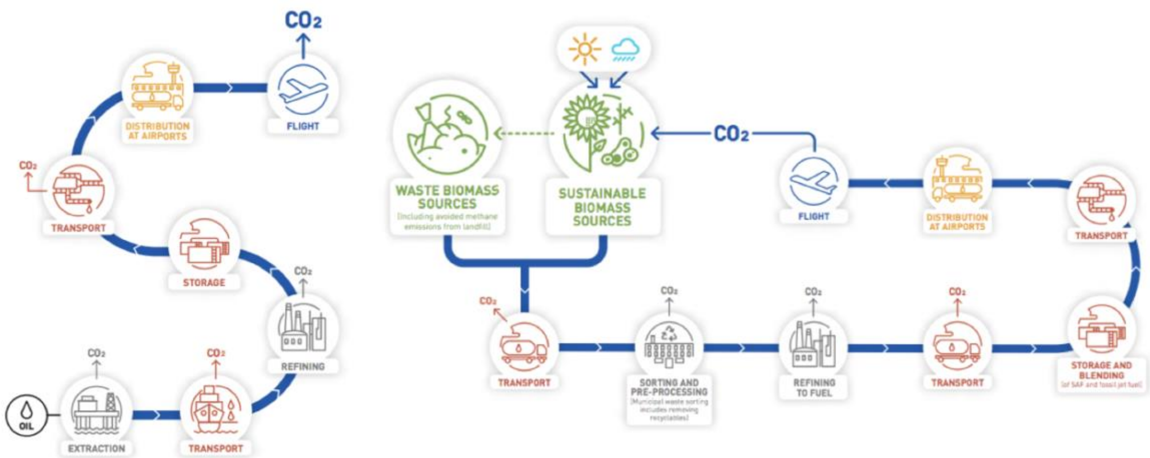

Figure 7: Carbon life cycle diagram for fossil jet fuel (left) and sustainable biofuel (right). Source: Adapted by the author from ATAG (2024)

SAFs are required to comply with strict quality and safety standards and ensure compatibility with the existing aircraft, infrastructures and fuel distribution systems, to be certified. This important characteristic is known as ‘drop-in’ capability, ensures a seamless integration of SAFs into the aviation fuel supply chain without requiring any modifications to aircraft, engines or ground facilities. Airlines have the possibility to integrate SAFs as a direct replacement for fossil-based fuels, allowing them to immediately reduce their carbon footprint and environmental impact without compromising operational efficiency or safety.

SAFs can offer diversification of fuel sources, reducing the industry's reliance on finite fossil fuel reserves and enhancing energy security. By using renewable feedstocks and sustainable production processes, SAFs contribute to preserve resources and promotes the principles of circular economy. The development and integration of SAF into aviation stimulates innovation and investments in the clean energy sector, contributing to economic growth and job creation, "positioning the European Union as a frontrunner in this upcoming industry" (NLR – Royal Netherlands Aerospace Centre & SEO Amsterdam Economics, 2021).

Despite all the potential benefits, the adoption of SAFs faces many challenges, such as cost-competitiveness, limited availability, and regulatory barriers. Ongoing collaboration among the industry stakeholders, governments and academia are addressing these challenges, contributing to research, development, commercialization and scalability of SAFs. As aviation is pushed to more sustainable practices and bigger environmental responsibility, SAFs are expected to play a key role in achieving carbon-neutral aviation in the future.

As mentioned in previous chapters, enhanced aircraft and engine designs, improvements in technology and optimized operational procedures and air traffic management systems will be essential to reduce carbon dioxide emissions in the aviation industry. But, the most significant impact will come from the use of Sustainable Aviation Fuels (SAFs). The numbers show that SAF production reached approximately 300 million liters in 2022, already representing 200% growth over the previous year. To have an idea of the size of the challenge, to achieve the target set for 2050, SAF production capacity will have to be expanded to about 450 Billion liters per year (IATA, 2021).

5.2 Technical Characteristics and Performance of Sustainable Aviation Fuels

To be considered ‘drop-in’ ready, SAF must comply with the quality attributes of conventional jet fuel, such as composition, volatility, fluidity, combustion, corrosion, thermal stability, contaminants, and additives, among others. The American Society for Testing and Materials (ASTM) is the organism responsible for guaranteeing the quality and safety standards applicable to Sustainable Aviation Fuel (SAF). ASTM D1655 is the document that establishes the global standards for conventional jet fuel, mandating the strict specification that have to be followed by producers of fuels used in commercial aviation (ASTM, 2023).

Another important document relevant on this subject is the ASTM D7566. Here, the regulator defines the quality requirements for each of the approved SAF production pathway. Every new SAF technology must go into the rigorous process of testing, according to ASTM D4054, to determine its compatibility with the requirements, before being certified. Certified SAF can then be blended with the conventional jet fuel in approved ratios, and the final product is then considered to comply with the ASTM D1655, meaning that it is a ‘drop-in’ fuel ready to be deployed into the existing infrastructure and being used on current aircraft. This process of SAF certification, based on ASTM standards, promotes trust in SAF safety and quality and eases the seamless integration into the aviation industry (ASTM, 2022).

Currently, the blending ratio of certified Sustainable Aviation Fuel (SAF) with conventional jet fuel is limited to a maximum of 50% depending on the production process. This is due to naturally low content of aromatics in SAF, while the currently used of nitrile O-rings in aircraft fuel systems require a minimum aromatic content of 8% in the fuel for proper lubricating characteristics. (Chevron, 2007) This will not be the case in the future, as the recent advancements in SAF conversion processes associated with the development of new fluorocarbon O-rings, that do not require the same quantity of aromatics, are expected to allow the use of 100% SAF by the year of 2030. (EASA, 2024b) Recently, a cooperation among Airbus, Rolls Royce and the German Aerospace Center (DLR) conducted a successful commercial flight using 100% Sustainable Aviation Fuel (SAF) derived from the HEFA pathway (Airbus, 2021).

The advantage of SAF compatibility with existing aviation infrastructure is evident. As a 'drop-in' fuel alternative, SAF can be blended with conventional jet fuels in different percentages according to the production method, enabling flexible and incremental integration into the aviation fuel supply chain. The compatibility ensures that airlines can start adoption of SAF immediately without requiring any investment in new aircraft or extensive and expensive modifications. As seen before, the ASTM D7566 established the specifications for SAF and the blending ratios possible with the current SAF available. Table 3 summarizes this information.

Sustainable Aviation Fuel (SAF) is engineered to match the energy density of conventional jet fuels, to allow for same aircraft range and efficiency. Producers use methods such as Fischer-Tropsch synthesis and Hydroprocessed Esters and Fatty Acids (HEFA) to achieve this characteristic. SAF is also required to have good combustion properties, like a high cetane number, leading to a more efficient burning and consequent reduced emissions, not only carbon dioxide but also other important polluters such as sulfur oxide or particulate matter. Flight conditions are demanding, with temperatures ranging between hundreds of negative and positive degrees Celsius, thus SAF must also demonstrate a strong thermal stability, resisting to decomposition at high temperatures or freezing at very low temperatures and preventing system blockages, ensuring reliability (ICAO, 2018).

5.3 Production Pathway of Sustainable Aviation Fuels

Considering the limited availability from renewable feedstocks to produce Sustainable Aviation Fuels (SAF), multiple pathways must be considered to achieve the low carbon emission goals of the aviation industry. As the demand for SAF raises, feedstocks become scarcer and all possible pathways must be explored and evaluated, in terms of maturity, costs, and environmental benefits associated. SAF can be divided into two primary categories, according their source, biofuels and synthetic fuels, described in more detail below. In this sub-chapter, we describe and evaluate the current state of the art in SAF production methods and examine emerging future technologies.

5.3.1 Biofuels

Nowadays, even when fuels are based in biological feedstocks, we use the broader term Sustainable Aviation Fuels (SAF). The nomenclature is used to avoid confusions with first generation of biofuels derived from crops such as corn, sugarcane, palm oil, rapeseed, and soybean, which are potential food sources for humans and animals, raised numerous concerns about potential alterations in agricultural land use, water consumption, and the impact on food prices. Today, to obtain certification from the American Society for Testing and Materials (ASTM), aviation fuels must make prove that they derive from sources that do not compete with food production and do not contribute to unsustainable practices, hence the term sustainable aviation fuel (SAF) is used.

In terms of the feedstock used, current technology enables sustainable aviation fuel production from a wide range of materials. The main feedstocks used currently are described below:

Waste oils and fats: Materials like used cooking oils, animal fats or other residual fats are the main feedstock used nowadays for SAF production. These materials are of high-value as feedstock because they do not compete with food production, avoiding the conflict fuel vs food. In reality this production method offers a valuable method of recycling waste products that would otherwise be disposed, making it a perfect example of circular economy. When processed, these oils and fats are converted into high-quality and high-value hydrocarbons that comply with the strict specifications and requirements of aviation fuel (ATAG, 2021a).

Municipal solid waste: Circular waste management is the base of this resource-efficient Sustainable Aviation Fuel (SAF) pathway. This pathway gives the dual benefit of waste management and renewable energy generation. MSW is the broad definition of everyday waste materials that are discarded by households and business, such as organic materials, plastics and non-recyclable materials. Employing advanced processes such as gasification and the Fischer-Tropsch synthesis, these waste materials can be converted into synthetic hydrocarbons suitable as aviation fuels. The use of MSW reduces environmental pollution and methane emissions, by diverting waste from landfills, while supporting circular economy by given a new life to waste, transforming it in a valuable resource (ATAG, 2021a).

Cellulosic waste: This waste material is derived from non-food plant material like agricultural residues and forestry waste. These materials are often abundant in nature and underutilized. This waste category includes material such as straw, wood chips, and other lignocellulosic biomass that can be transformed in sustainable aviation fuels. The conversion process of cellulosic waste into SAF is based on a series of advanced biochemical and thermochemical processes, such as hydrolysis, fermentation and gasification followed by Fischer-Tropsch synthesis. Like on the case of MSW, utilizing this type of waste as a feedstock has multiple benefits; not only it's a biomass that does not compete with food production, as it also decreases GHG emissions either in landfills or during the burning process (ATAG, 2021a).

Cover crops: Cover crops are typically grown during the off-season of agricultural rotations, offering the benefits of soil enhancement, erosion prevention and increased biodiversity. Plants like camelina, carinata and pennycress are full of seeds rich in oils that can be converted into SAF through processes like Hydroprocessed Esters and Fatty Acids (HEFA), process detailed on a later stage. These cover crops offer the advantage of not competing with food crops for arable land, as they can be integrated into existing agricultural systems without compromising food security. Another advantage is the fact that these crops can provide farmers with additional revenue while contributing to more sustainable practices (ATAG, 2021a).

Jatropha: This plant produces seeds with 30-40% of its mass in lipid oil (inedible) that can be processes into biofuels through the Hydroprocessed Esters and Fatty Acids (HEFA) pathway. Jatropha also avoids the conflict food vs fuel because it can be grown in a range of difficult soil conditions, arid and otherwise non-arable areas. The seeds are toxic either to humans or animals, therefore not used in the food industry (ATAG, 2021a).

Halophytes: Salicornia and Seashore Mallow are examples of this kind of plants that thrive in saline environments, like salt marshes and areas affected by sea spray. These species do not compete with food crops for land or fresh water because they can grow in conditions where other plants cannot. Their ability to produce oil-rich seeds makes them suitable for biofuel production via Hydroprocessed Ester and Fatty Acid (HEFA) process. One project conducted in the UAE showed the potential to integrate these cultures with seawater aquaculture, resulting in an integrated system that produces aquaculture fish and feedstock for fuels (ATAG, 2021a).

Algae: One of the most promising feedstocks for the future of biofuels. Algae are microscopic plants that can be grown almost everywhere, from plastic sleeves (microalgae) to saline or even polluted waters (macroalgae). Like other plants, algae absorb CO_2 through photosynthesis, which can be particularly advantageous when integrated with industrial operations that emit this gas. The unique characteristic of algae is their rapid growth rate, some species of algae are able to double their area in approx. 24h (and the effect is exponential). There are also studies showing that algae can generate up to 15 times more oil per square kilometer than any other comparable feedstock. Algae are also adapted to grow in areas unsuitable for growing food, referred to as marginal lands. The economic viability of algae-based biofuel production can be enhanced with the generation of valuable sub-products, such as proteins, pigments, and bioactive compounds (ATAG, 2021a).

In terms of the technologies available to process feedstock into Sustainable Aviation Fuel (SAF) there are currently seven pathways certified by ASTM. Each of the different pathways present different benefits and challenges, either in terms of the feedstock availability and price, either in terms of processing complexity and costs, or in terms of carbon emission reduction. Some of these pathways may be more suitable in certain parts of the globe, depending on feedstock availability, processing capacity or price of energy. However, considering that currently the demand for SAF surpasses in great quantity the supply, most likely aviation will have to rely on all pathways available and certified, despite the cost difference. In this sub-section we describe the most relevant pathways approved by ASTM as detailed in the ASTM D7566 (ASTM, 2022).

Fischer–Tropsch: The Fischer-Tropsch (FT) is one of the most important processes used to produce high-quality Sustainable Aviation Fuel (SAF). The process if flexible and can rely on a variety of carbon-rich feedstocks, like biomass and municipal solid waste and involves two main steps: gasification, in which the feedstock in converted into syngas (a combination of hydrogen and carbon monoxide) and Fisher-Tropsch synthesis, were the gas is catalytically transformed into long-chain hydrocarbons. On the final stage, these hydrocarbons are then refined into jet fuel or other liquid fuels. The FT offers remarkable feedstock flexibility and environmental benefit, but the process is capital-intensive, meaning that its economic viability is dependent on feedstock cost and production scale. A variation of this process is Fischer-Tropsch-Synthesized Kerosene with Aromatics (FT- SKA), where aromatics are added to the sustainable fuel (Cabrera & Melo de Sousa, 2022).

Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene: HEFA-SPK is the main process used to produce SAF nowadays by converting lipids into hydrocarbons. The feedstock for HEFA is typically a triglyceride, such as animal fats (tallow), used cooking oil, waste FOGs (fats, oils, and grease), and oil from algae or plants such as Camelina or Jatropha, rich in oils as discussed before. The process has four main stages: On a first stage the biogenic material is purified; the second stage is called deoxygenation, process in which hydrogen and catalysts are used to remove oxygen from oil; in the third stage the resulting hydrocarbons are cracked and isomerized to achieve the desired chain-length; and on the last stage the hydrocarbons are distilled and separated, and a jet fuel designated HEFA-SPK is obtained (Cabrera & Melo de Sousa, 2022).

Synthesized Isoparaffins Produced from Hydroprocessed Fermented Sugars (HFS- SIP): This process is a direct of sugar to hydrocarbons and uses genetically modified microorganisms (such as algae, bacteria, and yeast) to convert sugars into a substance known as farnesene, a Synthetic Iso-Paraffine (SIP) that can be converted into a product with as good characteristics as aviation fuel. The process was certified in 2014 and only permits blending ratios up to 10%. Currently the process uses only biological routes with exclusive use of conventional sugars, although cellulosic sugars are being tested. The process of converting lignocellulosic sugars into fuel through Direct Sugar to Hydrocarbon (DSHC) is complex, energy-intense and has low efficiency, making DSHC the most expensive alternative route, with low viability (Bauen et al., 2020).

Alcohol-to-Jet (AtJ): Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK) is a type of Sustainable Aviation Fuel (SAF) produced from alcohols, such as ethanol or isobutanol made from sugar/starch-bearing plants. The ATJ pathway is a multi-step chemical process that involves: dehydration of alcohols to create olefins, which are then oligomerized to form long-chain hydrocarbons; these hydrocarbons suffer then a process hydrogenation and other refining steps, to produce synthetic paraffinic kerosene, chemically similar to conventional jet fuel. This pathway is particularly versatile because it can utilize various alcohol feedstocks, including those derived from biomass, industrial waste or other innovative processes. ATJ-SPK has been certified in 2016 by ASTM D7566 specification for use in aviation, allowing blending rates of up to 50% with conventional jet fuels (GEVO, 2022).

Others: More recently ASTM approved two new methods for producing biofuels, Cathalytic Hydrothermolysis Jet (CHJ) and Hydroprocessed Hydrocarbons (HC-HEFA). The CHJ process involves the conversion of lipid-based feedstocks, such as vegetable oils or animal fats, into jet fuel through a process that involves the use of water at very high temperature and pressure, together with a catalyst and a CH reactor, to break down fats and oils into hydrocarbons. Those hydrocarbons are then refined into jet fuel chemically similar to conventional fossil-based aviation fuel. The HC-HEFA method converts oils from Botryococcus braunii algae into jet fuel. This novel approach is an advanced variant of traditional HEFA and has a blending limit of 10% with conventional fuels. This method is very relevant due to the great advantages of algae as a feedstock, as studied before. These two methods were introduced in ASTM D7566 in 2020 (IATA, 2024a).

The following table summarizes the different biofuels pathways approved by ASTM for use in aviation, showing the various conversion processes, possible feedstocks, and blending limits.

Table 3: List of the Biofuels pathways approved by ASTM. Source: ASTM (2022)

Abbreviation	Conversion process	ASTM reference	Possible Feedstocks	Blending ratio by volume
FT	Fischer-Tropsch hydroprocessed synthesized paraffinic kerosene	ASTM D7566 Annex 1	Coal, natural gas, biomass	50%
HEFA	Synthesized paraffinic kerosene from hydroprocessed esters and fatty acids	ASTM D7566 Annex 2	Bio-oils, animal fat, recycled oils	50%
SIP	Synthesized iso-paraffins from hydroprocessed fermented sugars	ASTM D7566 Annex 3	Biomass used for sugar production	10%
FT-SKA	Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources	ASTM D7566 Annex 4	Coal, natural gas, biomass	50%
ATJ-SPK	Alcohol to jet synthetic paraffinic kerosene	ASTM D7566 Annex 5	Biomass from ethanol or isobutanol production	50%
CHJ	Catalytic hydrothermolysis jet fuel	ASTM D7566 Annex 6	Triglycerides such as soybean oil, jatropha oil, camelina oil, carinata oil, and tung oil	50%
HC-HEFA-SPK	Synthesized paraffinic kerosene from hydrocarbon-hydroprocessed esters and fatty acids	ASTM D7566 Annex 7	Algae	10%
FOG Co-processing	Fats, Oils and Greases Co-processing	ASTM D1655 Annex A1	Fats, oils, and greases (FOG) from petroleum refining	5%
FT Co-processing	Fischer-Tropsch Co-processing	ASTM D1655 Annex A1	Fischer-Tropsch (FT) biocrude as an allowable feedstock for petroleum co-processing	5%

Given the limitations of bio-based feedstocks, attention is increasingly turning to synthetic fuels.

5.3.2 Synthetic Fuels

Fuel referred to as eSAF, is predominantly generated using Power-to-Liquid (PtL) technology, which involves combining green hydrogen with CO_2 to produce synthetic fuel. Recent advancements have led to the development of cutting-edge technology that offers a sustainable replacement for fossil fuels, known as 'solar fuels'. These synthetic fuels are created directly from solar energy within a special reactor and represent a promising alternative to aviation fuels.

5.3.2.1 Power to Liquid (PtL)

The Power-to-Liquid (PtL) method for production of sustainable aviation fuel (SAF) involves the conversion of electric energy from renewable sources - such as photovoltaic, wind power or other - water, and captured carbon dioxide (CO_2) into liquid hydrocarbons. As described by the diagram below, this method uses renewable electricity to drive water electrolysis and generate green hydrogen (H2). The hydrogen is then combined with CO_2 coming from heavy industries or directly captured from the air (DAC) to produce a gas known by syngas. Syngas is then transformed, through a series of chemical reactions - either through Fischer-Tropsch (FT) synthesis or the methanol-to-jet (MtJ) synthesis - into liquid hydrocarbons, which are then refined into a synthetic sustainable aviation fuel. This process is in an early stage of development. These fuels emit as much CO_2 as the one captured beforehand making it almost carbon-neutral, as shown in figure 8 (Batteiger et al., 2022a).

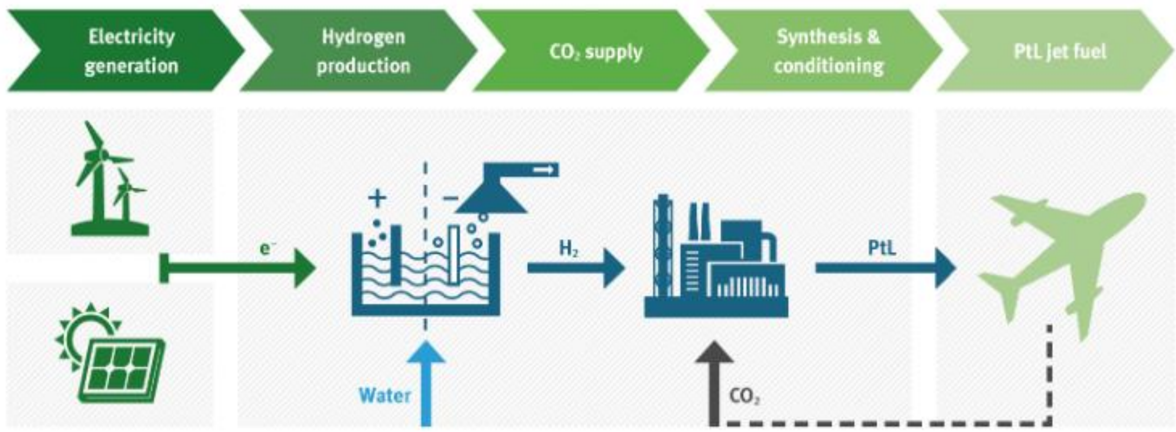

Figure 8: Conceptual diagram of Power-to-Liquid process. Source: Batteiger et al.(2022)

5.3.2.2 Sun to Liquid (StL)

Sun-to-liquid fuels, also known as solar fuels, are an innovative solution with potential to create very carbon-neutral liquid fuels in the future. In a very early stage of development, these fuels can make a contribution to energy security and environmental sustainability. Solar fuels are synthetized by a direct conversion of solar energy, water and carbon dioxide into an energy-dense hydrocarbon that only release as much CO_2 into the atmosphere as was used for their production, making them carbon-neutral liquid fuels (Synhelion, 2024b).

The solar fuel production process is based on four key steps:

1. A mirror field that directs the solar radiation into the solar receiver
2. A solar receiver converts solar radiation into heat at temperatures above 1500°C
3. A thermochemical reactor that receives the heat, water and CO_2 and produces syngas, the precursor to synthetic liquid fuels
4. A thermal energy storage unit that enables continuous day-and-night operation

As documented on the picture below, solar radiation is concentrated on the receiver, using a mirror field, and converted into very high-temperature heat. This heat is used by a special thermochemical reactor that receives also water (for H2) and carbon dioxide and produces syngas (a mixture of H2 and CO). Syngas is then processed through chemical reactions (Fischer-Tropsch process) into liquid fuels, including jet fuel. Excess heat is stored in thermal energy storage unit to enable continuous operation. The world's first industrial-scale solar fuel plant is already in operation, in Germany (Synhelion, 2024a).

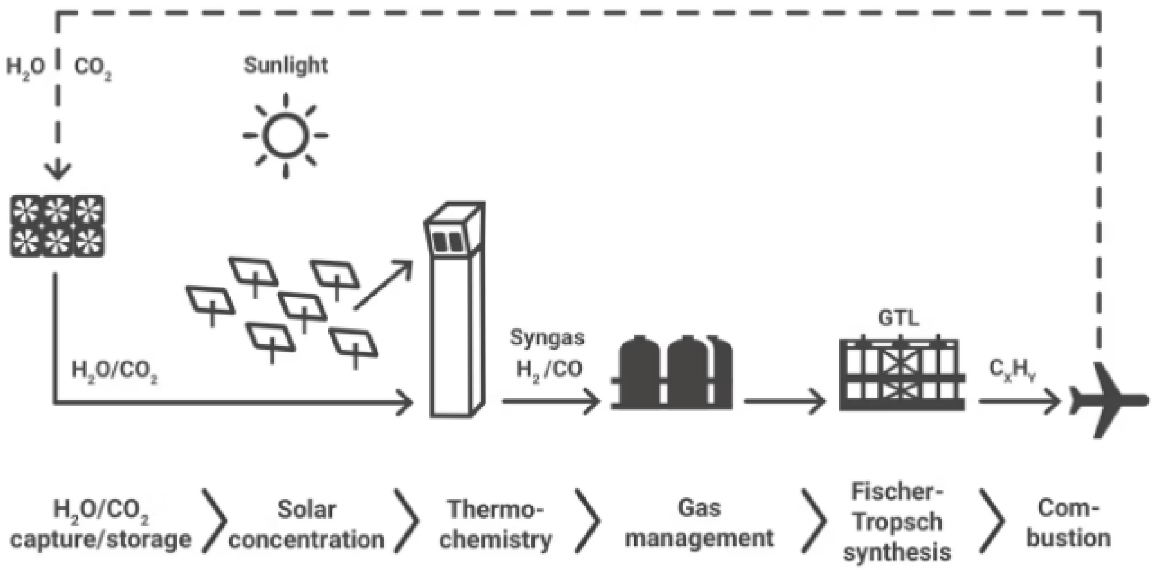

Figure 9: Conceptual diagram of Sun-to-Liquid process. Source: Synhelion (2024)

5.4 Techno-economic Analysis of Sustainable Aviation Fuels

Sustainable Aviation Fuel (SAF) generally trades at a much higher price than conventional fossil-based jet fuels. Depending on the feedstock used, production method and market dynamics, SAF can be priced somewhere between three to five times the price for traditional jet fuel. On our research, we found that SAF price fluctuates between $1000 to $3000 per metric tonne, where conventional jet fuel typically ranges from $600 to $800 per metric tonne (EASA, 2025).

SAF's higher priced is largely due to the current small scale of production associated with production processes complexity and feedstock availability. However, as the investment in R&D increases and technology progresses, new feedstock options become available and, with time, economies of scale will permit to decrease prices over time. In order to make SAF more price competitive with fossil fuels, government incentives, carbon pricing mechanisms and airlines commitments to sustainability are key factors, these factors will affect the future SAF price trajectory.

The economic aspects of Sustainable Aviation Fuels are intimately connected with technological developments, environmental regulation, market dynamics and consumer behavior. With SAF price ranging from three to five times the price of fossil fuels, and fuel accounting for approximately 25% of airlines' total operating costs, it is imperative to find a delicate balance between sustainability and economic viability for airlines already operating on very tight margins. When discussing sustainability, it is very important to consider it in terms of three dimensions: environmental, social and economic (Doganis, 2019).

Studies show that the HEFA pathway is currently the most cost-effective and the most mature method to produce Sustainable Aviation Fuel. The capital expenditures (CAPEX) are the lowest compared with any other SAF pathway, this is due to the fact that HEFA is a mature technology, the conversion process is simpler and shorter and it can leverage existing infrastructure. The production costs are mainly driven by the cost of feedstocks, which remains high. HEFA-derived SAF is competitively well positioned due to its high yield and relatively low technological risk. The biggest constraint to scale production is the limited availability of suitable feedstocks, which are also in high demand by other sectors (Pavlenko et al., 2019).

The second most cost-effective conversion process is the Fischer-Tropsch pathway, particularly for fuels derived from Municipal Solid Waste (MSW). The primary costs associated with this process comes from upfront capital expenditures, which are higher due to a higher degree of uncertainty and potential yields. CAPEX may account from 81% of the cost, in the case of gasification-FT fuels produced from MSW, to 60% of the cost in the case of gasification-FT fuels produced from agricultural residues. Economies of scale can dilute the CAPEX investment with time, but this remains limited by the availability of feedstock (Pavlenko et al., 2019).

Regarding the PtL pathway, research shows that the biggest challenge for PtL SAF is the high cost of green hydrogen and CO_2 capture processes, and the high energy-intensity nature of the process. However, PtL SAF is highly scalable and capable of achieving the highest carbon emission reductions if powered by renewable energy sources. Its economic viability is likely to improve as the price of renewable energy drops and if strong policy support is in place, such as carbon pricing and subsidies for low-carbon technologies. This technology still has some uncertainty but can be more cost-effective in areas of the world where abundant and affordable renewable electricity sources exists (Pavlenko et al., 2019).

The alcohol-to-jet (ATJ) pathway is a promising but currently more expensive method for producing Sustainable Aviation Fuel (SAF). This method offers the advantage of using existing industrial infrastructure and a variety of alcohol feedstocks, but its economic viability is challenged by the high costs of alcohol production, the energy- intensive nature and complexity of the conversion process and its relatively low yields. This process has potential for higher economic viability through improvements in technology, economies of scale, development of more cost-effective feedstocks, such as non-food biomass and waste alcohols (Pavlenko et al., 2019).

Synthesized Iso-Paraffins (SIP) pathway indicates that while it offers a sustainable method for producing Sustainable Aviation Fuel (SAF), it is currently the most expensive alternative. With high CAPEX costs and very complex and energy-intensive processes of fermentation and hydroprocessing, the costs of production reach very high values. Also contributing to this is the cost of feedstock, especially when using conventional sugars, which have high price volatility and compete with food products. Another factor disincentivizing its production is the fact that it can only be blended up to 10% with conventional fossil fuel. Future reductions in its price are dependent on biotechnology developments, use of low-cost cellulosic materials and the scaling up of production processes to achieve economies of scale (Pavlenko et al., 2019).

The following graph presents a summary of the levelized costs of production for the Sustainable Aviation Fuel (SAF) conversion pathways studied.

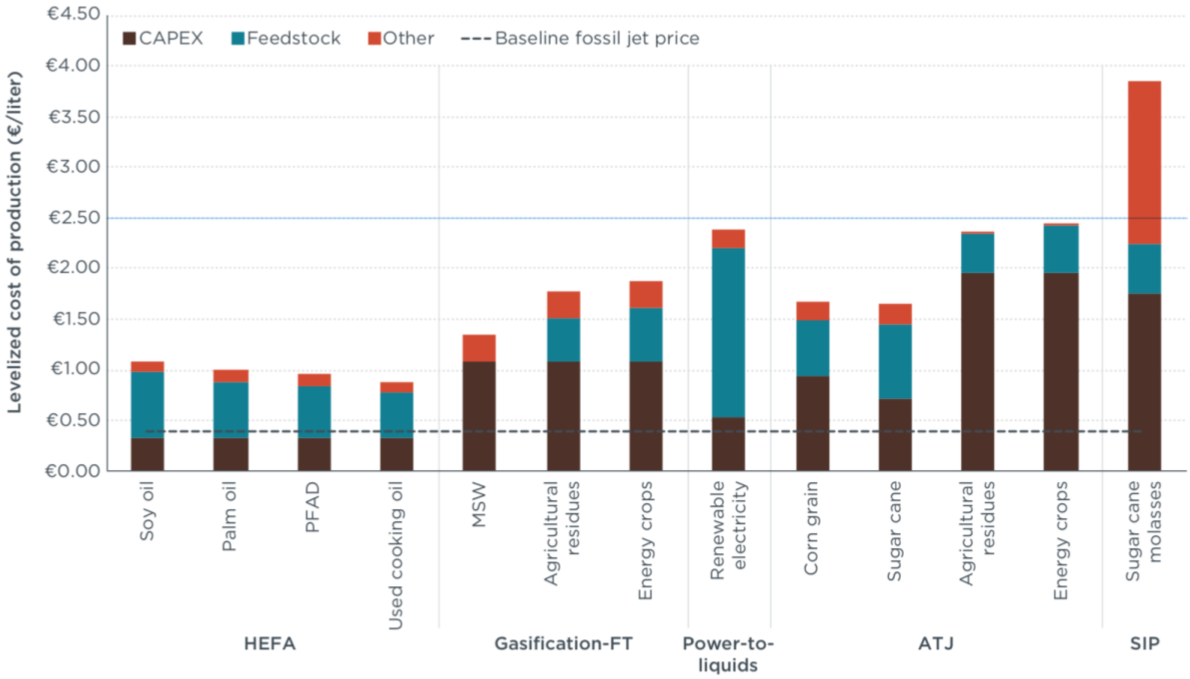

Figure 10: Levelized costs of production of the different pathways (€/liter). Source: Pavlenko et al. (2019)

Our literature review shows the evidence of HEFA being the state-of-the-art commercial Sustainable Aviation Fuel (SAF) able to compete, in price terms, with conventional jet fuel prices. Currently, FT and AtJ are significantly more expensive than HEFA, but the feedstock flexibility of these two routes has the potential to compensate for CAPEX investment. The increasing deployment of the cost-effective Municipal Solid Waste (MSW) as feedstock associated with technological development and inherent scale effects will likely make FT and AtJ implementation more cost-competitive and viable in the future. Although the PtL route in not currently cost-competitive, further techno-economic analysis consistently show its high future potential, owing to its virtual unlimited feedstock availability, potential very high lifecycle carbon emission reductions and significant cost-reduction potential driven by decreasing price of renewable energy and economies of scale.

Sustainable Aviation Fuel (SAF) are in the early stage of its development. And, as any other recent technology, SAF requires continued innovation, substantial investment in research and development and a legislative framework that provides the right incentives to achieve cost parity with conventional fuels. However, cost considerations are not the only factor to look at when we evaluate SAF. Environmental impacts should also be integrated to align decisions with broader goals. On the next sub-chapter, we present an environmental assessment of SAFs.

5.5 Environmental assessment of Sustainable Aviation Fuels

As demonstrated by our techno-economic analyses, Sustainable Aviation Fuels (SAF) are still not financially competitive with fossil jet fuels. However, their environmental benefits are undeniable. In this sub-chapter we look into the environmental assessment of SAF, quantifying the greenhouse gas (GHG) emissions of each technology. For a proper evaluation, we must look into emissions produced from the feedstock production to the final use of the product, so-called Life Cycle Analysis (LCA). Greenhouse emissions are typically measured in grams of carbon dioxide equivalents per megajoule of fuel used (g CO_2eq/MJ). When performing an analysis of the production methods for Sustainable Aviation Fuel (SAF) the lifecycle assessment (LCA) accounts nor only for direct emissions, but also indirect and induced emissions, trough the incorporation of Indirect Land Use Change (ILUC).

The carbon intensity from conventional jet fossil fuel ranges from 85-95 g CO_2eq/MJ, coming approximately 80% from the combustion and the remaining 20% are related to fuel extraction, refining and transportation. The International Civil Aviation Organization’s (ICAO) policy for the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) uses a baseline of 89 g CO_2eq/MJ (Pavlenko & Searle, 2021).

As mentioned, HEFA is currently the most mature Sustainable Aviation Fuel (SAF) pathway with the lowest production costs among all available technologies. From an environmental point of view, total HEFA emissions depend on the feedstock used for production. The lowest lifecycle greenhouse (GHG) emissions are verified when produced via used FOGs (fats, oils and greases) because this process avoids emissions from crop production, whereas HEFA produced using virgin vegetable oils has higher well-to-wing GHG emissions due to crop production and indirect land-use change (ILUC). Emissions from this process not only vary with the feedstock used, but also with the costs of production of hydrogen, a key component of the process, and energy consumed at the refinery, meaning that the sources of H2 and electricity have a significant impact on the emissions. When compared with tradition jet fuels, HEFA emission saving ranges from 25-85%, with Renewable Energy Directive (RED II) providing typical values ranging from 15-62 g CO_2e/MJ (Pavlenko & Searle, 2021).

The Fischer-Tropsch pathway has remarkable emission reduction characteristics. Studies suggest that the emission savings can range from 85–95% of those of the conventional jet fuel, leading to a very low value of 5–12 g CO_2eq/MJ. This process can achieve the lowest emissions when the feedstocks are municipal solid waste (MSW) or forestry residues. The emissions from MSW depend on their non-biogenic content (ICAO, 2022a).

Alcohol-to-jet (AtJ) pathways has a tendency to have higher greenhouse gas (GHG) emissions than both HEFA and Fischer-Tropsch (FT) fuels, due to the energy-intensive biochemical processes of alcohol production. Starch crops have less potential for GHG emissions reduction due to its lower growth rate and processing efficiency; while sugary crops, lignocellulosic crops and residues have much more potential for emission mitigation due to the minimal emissions associated with fertilizer use and feedstock cultivation. Using industrial carbon-containing gases have obvious benefits, but some significant emissions related to the energy required for gas compression. When compared with fossil fuels, GHG emission savings from AtJ fuels can substantially vary, ranging from 26-73% depending on the feedstock used, with ICAO using the reference value of 48.5 g CO_2eq/MJ (Pavlenko & Searle, 2021).

E-fuels offer the greatest potential for mitigating greenhouse gas emissions in the aviation industry. Studies indicate that the overall direct GHG emissions of an e-fuel production pathway from renewable electricity and captured CO_2 are approximately 1 g CO_2eq/MJ, providing more than 95% emission savings compared with the fossil fuel reference (Batteiger et al., 2022a). As large quantities of renewable electricity are needed for the production of this type of fuel, the LCA studies integrating the emissions derived from the construction of the production facilities and power stations indicates a carbon footprint of 5-10 g CO_2eq/MJ (Concawe and Aramco, 2022). The same report highlights the fact that environmental performance of e-fuels is highly dependent on the source of electricity, being the use of renewable electricity a clear prerequisite for the environmental viability of this pathway.

The following chart shows the total GHG equivalent emissions for the different SAF pathways (in g CO_2eq/MJ), including direct emissions and indirect land use change (ILUC) emissions, compared to emissions from conventional jet fuel (Detsios et al., 2023).

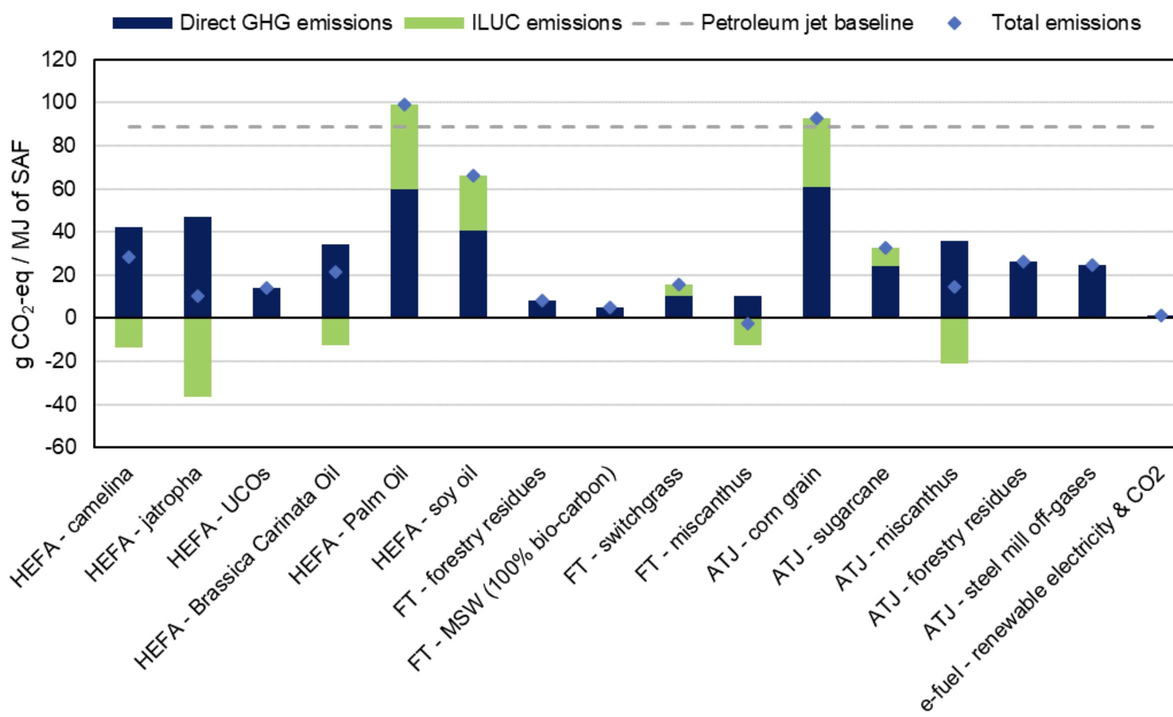

Figure 11: Direct and ILUC emissions of SAF. Source: Detsios et al. (2023)

5.6 Regulatory Framework for Sustainable Aviation Fuels

The regulatory framework affecting Sustainable Aviation Fuels (SAF) deployment has substantially evolved over time. Regional and International institutions have aligned efforts into a series of agreements aimed at mitigating greenhouse gas emissions and promoting alternative, cleaner energy sources within the aviation sector. In this section we expand, on a chronological order, on the most relevant regulations that cumulatively increased the global commitment to more sustainable practices in the aviation industry.

Kyoto Protocol (1997)

Adopted in 1997 at the COP3 in Koyo, Japan, and entering into force in 2005, was the first international treaty focused on the mitigation of greenhouse gas (GHG) emissions. The Kyoto protocol operationalizes the United Nations Framework Convention on Climate Change (UNFCC) by committing industrialized countries to transition their economies to limit and reduce GHG according agreed individual targets. This protocol only binds developed countries as it recognizes that they are responsible for the majority of the emissions. The aviation industry was not initially included within the protocol's binding targets, but the Kyoto Protocol established a foundation for subsequent deliberations on aviation emissions (UN, 1997).

Renewable Energy Directive (RED I) (2009)

Adopted in 2009, The European Union's Renewable Energy Directive (RED I) was the first significant advancement in the EU's effort to increase the share of renewable energy used in the region. RED I established a target of 20% of the energy used in 2020 coming from renewable sources, with a specific target of 10% for the transport sector. Although Sustainable aviation Fuels (SAF) were not referred, this directive established a broad regulatory framework that incentivize the development of renewable technologies, including biofuels for aviation. With the adoption of RED I the share of renewable energy consumed in EU increased from 12.5% in 2010 to 23% in 2022 (EU, 2009).

EU Emissions Trading System (EU ETS) (2012 for Aviation)

The European Union Emissions Trading System (EU ETS) emerged, in 2005, as the world's first carbon market. In 2012 the system was extended to carbon dioxide (CO_2) emissions from aviation within the European Economic Area (EEA). Under the EU ETS, airlines are required to monitor, report and verify their emission and surrender a sufficient quantity of emission allowances to cover these emissions. The system creates the incentives to efficiency and adoption of sustainable practices, including the use of the low-carbon Sustainable Aviation Fuel (SAF) as alternative to fossil fuels (EU, 2014).

Paris Agreement (2015)

The Paris Agreement is a legally binding international treaty on climate change. Adopted at the UN Climate Change Conference (COP21) in Paris, France, in 2015, it is a landmark international treaty because it brings all nations together to combat climate change. Its overarching goal is "to limit the global temperature increase to 1.5°C above pre-industrial levels". Although it does not explicitly target aviation, the Paris Agreement emphasizes the need for all sectors of the economy to contribute to global emissions reduction, including aviation. The agreement has influenced national and regional policies as part of a broad decarbonization strategies, including the promotion of SAF (UN, 2015).

Renewable Energy Directive II (RED II) (2018)

The European Union implemented a revised Renewable Energy Directive (RED II), which became effective in 2018, as a response to the Paris Agreement. RED II adopted a more ambitious target of 32% renewable energy use in the EU by 2030. The directive gave a step forward to facilitate the adoption of Sustainable Aviation Fuels (SAF), by introducing a multiplier factor of 1.2 for sustainable aviation fuels that do not compete with food production, as a way to increase the incentives to their production and use. RED II was a crucial stimulus to promote SAF in the European aviation sector (EU, 2018).

Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (2021)

The International Civil Aviation Organization (ICAO) developed CORSIA in 2021 as the first global market-based measure to address CO_2 emissions from international aviation. To take forward ICAO goals, CORSIA mandates that the airlines must offset any emissions exceeding 2020 levels through the acquisition of carbon credits or the utilization of SAF. The actual emissions baseline is 2019, due to the COVID19 pandemic effects on the emissions of 2020. This scheme was designed to achieve carbon-neutral growth in international commercial aviation, and is complementary to regional initiatives such as the EU ETS (ICAO, 2024).

Fit for 55 Package (2021)

This ‘European climate law’ is part of the European Green Deal, and it was introduced by the European Commission in 2021. This deal puts into law the objectives of reducing greenhouse gas (GHG) emissions by at least 55% by 2030, and for the EU to achieve climate neutrality by 2050. This package also included substantial revisions to RED II, including the increased target of 40% renewable energy share by 2030 and strengthened the incentives for sustainable aviation fuel (SAF) production and utilization. In this regard, the package introduced the ‘ReFuelEU Aviation’, mandating SAF blending obligations at European Union airports, starting with a minimum of 2% in 2025 and progressively increasing over time. The mandates also include minimum quantities of synthetic fuels (e-Fuels) required, as shown in the following graph (EU, 2021).

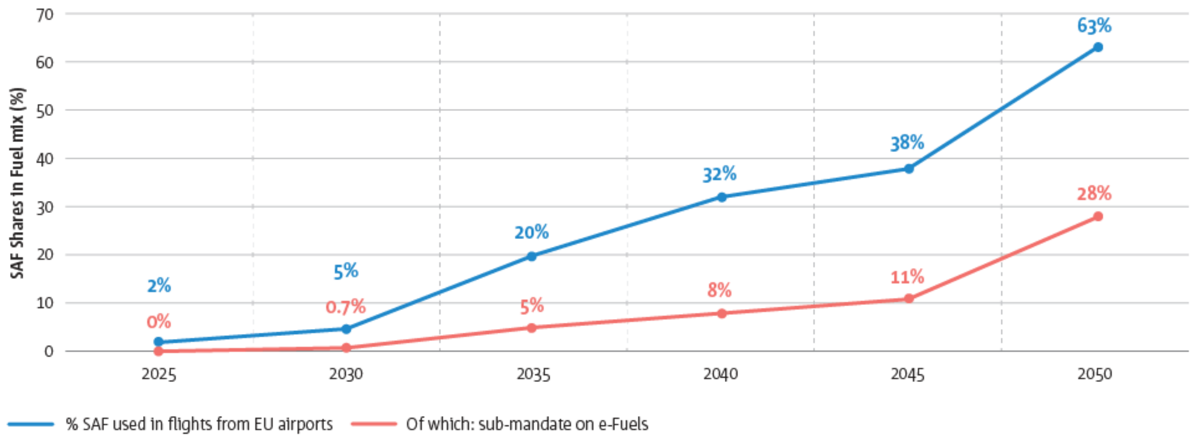

Figure 12: SAF and e-Fuel mandates in EU. Source: ReFuelEU Aviation Initiative (2021)

The regulatory has progressively evolved from initial international agreements, such as the Kyoto Protocol, to more targeted and binding regulations, like RED II, CORSIA, and the 'Fit for 55 package'. These regulations collectively contribute to the reduction of the aviation's carbon footprint, assuring the sector's contribution to global climate goals. The future developments of these frameworks will be critical to increase the viability of SAF and ensuring that its implementation contributes to the long-term sustainability in aviation.

5.7 Future Prospects and Challenges

The future of Sustainable Aviation Fuels (SAF) presents both significant opportunities and considerable challenges. Advancements in production technologies, particularly in feedstock processing and the development of synthetic fuels, have the potential to expand the availability of SAF, as aviation seeks to reduce its carbon footprint and transition to more sustainable operations. These innovations, together with improved production efficiency, can lead to increased scalability and cost reductions. However, the current SAF production capacity is far below the levels required to have a meaningful impact on global aviation emissions. Overcoming this limitation will require substantial research and investments in technology and production facilities to increase global production, distribution and storage of these fuels.

Economic viability remains a major constrain in the widespread adoption of SAF. Currently, SAF is considerably more expensive than conventional jet fuel due to its high costs of production linked to limited economies of scale. Addressing this cost gap will require not only the investments referred beforehand but also market-based mechanisms, such as EU ETS and CORSIA, and additional governmental support in the form of subsidies, tax incentives and public-private partnerships.

The regulatory frameworks play a key role in the future of SAF development. The European Union’s legislation has already set the stage for an increase adoption of SAF, by introducing blending mandates, as those imposed by the ‘ReFuelEU Aviation’. A major challenge is to achieve global harmonization of the regulations to ensure a smooth integration of SAF into global operations, and to avoid market fragmentation and risks such as carbon leakage. Global agreements on SAF standards and verifications can ease international trade and broader adoption, but reaching a consensus across regions with diverse priorities remains a huge challenge.

As an example of an innovative solution contributing to the adoption of Sustainable Aviation Fuel (SAF), emerges the ‘book and claim’. This system tackles the logistic problem of adopting SAF, by allowing airlines to buy SAF and claim its environmental benefits without the need of physically use the fuel on specific flights. The mechanism decouples SAF consumption from production, enabling companies to support SAF production in regions where it is the most cost-effective, even if they do not operate in those regions. The ‘book and claim’ system addresses the problem of limited supply of SAF, facilitating the market participation of the companies without the logistical problem (and associated emissions) of physically transporting SAF. At the end of the day, what matters most is the effective global reduction of emissions, regardless of where they occur. This system requires a robust verification system to ensure transparency and trust, preventing double counting of the environmental benefits (RSB, 2024).

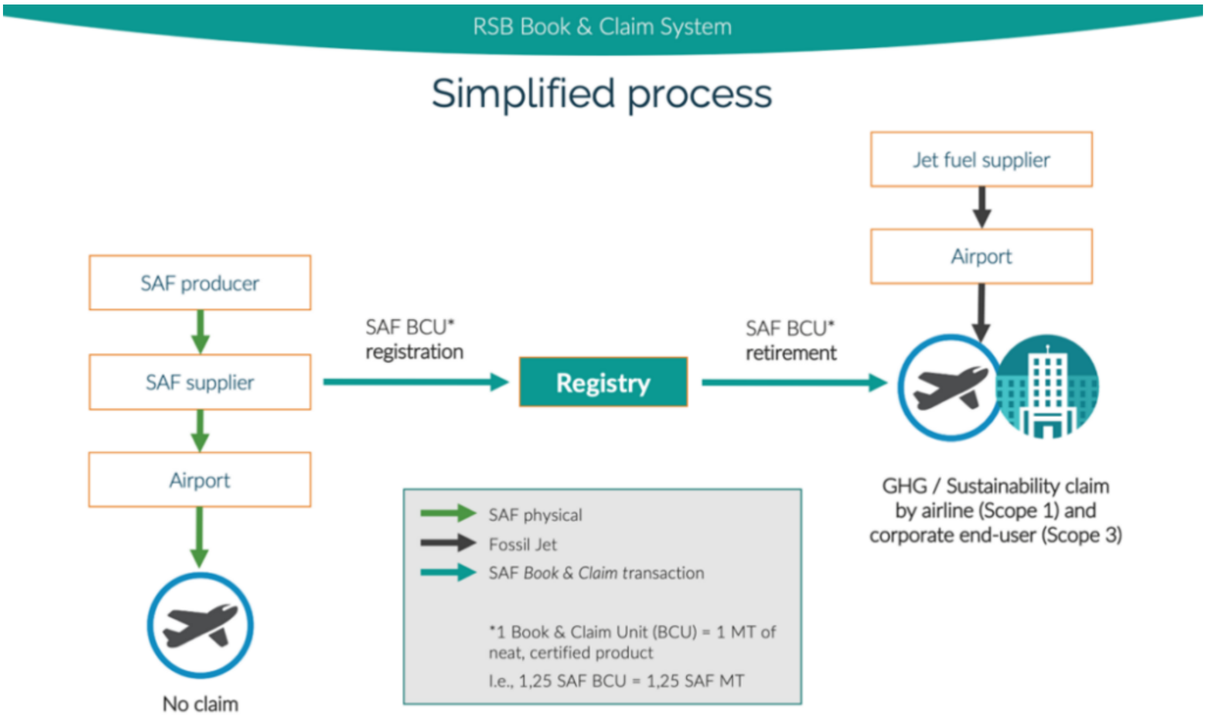

Figure 13: Book and Claim process. Source: RSB (2024)

While Sustainable Aviation Fuels (SAF) offer a promising pathway to decarbonize aviation, its long-term viability depends on its ability to respect environmental and social concerns. On one hand, SAF production must not cause deforestation, biodiversity loss, or conflict with food production. On another hand, producers must ensure fair practices across production chain, especially in developing countries. These are requisites to achieve both environmental sustainability and social responsibility while SAF scales up.

Another important characteristic of SAF is its market acceptance and consumer trust. Airlines must keep a clear and realistic communication relative to environmental benefits of SAF, while addressing client's concerns about increasing ticket prices. Public awareness remains low, showing the need for clear communication and strategic marketing. SAF technology continues to develop, but supportive policies, economic incentives and other mechanisms (e.g., 'book and claim') must keep in place. Only through a synergy among governments, regulators, airlines, and consumers, can SAF be successfully integrated into commercial aviation as a key pillar with a meaningfully contribution to a more sustainable future.

6 Fourth Pillar - Market-Based Mechanisms

As previously discussed, the aviation sector is exceptionally difficult to decarbonize and, therefore market-based mechanisms must be part of solution (Rogelj et al., 2015). To achieve net-zero emissions from commercial aviation by 2050, new technologies, efficient operations and Sustainable Aviation Fuels (SAF) alone are not sufficient. According to ICAO even with the implementation of these measures, approximately 6% of CO_2 emissions from aviation will still need to be compensated (ICAO, 2022b).

6.1 Addressing Negative Externalities through Economic Incentives

Economists view emissions as a problem of negative externalities, where the costs of pollution or environmental damage are not reflected in the market prices. Negative externalities arise when the production or consumption of a good or service imposes a cost on third parties that are not part of the transaction. Economists argue that the market alone does not address these externalities efficiently because polluters do not incur on the full cost of their actions. In these cases, interventions are often recommended to internalize the externalities, creating the incentives to cleaner production methods. These interventions can assume various forms, such as taxes, subsidies, tradable emission allowances or mandates. By pricing externalities, these measures help align private incentives with broader social welfare, when more sustainable and environmentally responsible outcomes are desirable (Samuelson & Nordhaus, 2005).

Incentives are used as a tool to motivate individuals or entities to engage in certain behaviors to achieve the desired positive outcomes, by modifying the balance between the costs and benefits associated with particular decisions. Economic incentives can take various forms and be employed across diverse sectors to encourage socially beneficial actions, promote economic growth or address specific challenges, like in this case. Carbon pricing mechanisms have emerged as significant economic incentives to promote emissions reduction. A higher carbon price simultaneously performs four critical functions: it signals consumers to adjust behavior, it incentivizes producers to innovate, it establishes clear market incentives for low-carbon alternatives, and it serves as a decentralized information system that aligns choices across the economy. In this chapter we explore how market-based mechanisms like CORSIA or EU ETS can help achieve net-zero in international aviation by the year of 2050 (W. Nordhaus, 2013).

6.2 Key International Agreements on Carbon Reduction

International agreements are the foundations for the creation and development of the carbon-pricing mechanisms. In this sub-chapter we analyze the main international agreements relevant to the implementation of these mechanisms in the aviation sector.

The Kyoto Protocol (1997): This international agreement established the first framework for mandatory emission reduction targets for developed countries. From this protocol arise the concept of Clean Development Mechanism (CDM) allowing countries with emission-reduction commitments to implement emission-reduction projects in developing countries, earning Certified Emission Reduction (CER) credits, each equivalent to one tonne of CO_2, that can be counted as meeting Kyoto protocol's targets (UN, 1997).

The Paris Agreement (2015): This important international agreement, stablished in 2015, took a step forward to the global climate action. This agreement urges all the participant nations to establish Nationally Determined Contributions (NDCs) to allow for higher ambition in their mitigation actions to promote a sustainable development and advocates carbon-pricing mechanisms as a mean of achieving these goals. The article 6 of the Paris Agreement promotes a structure for international cooperation via carbon markets which has incorporated mechanisms for the transfer of mitigation outcomes between nations (UN, 2015).

6.3 Emissions Trading Systems and Carbon Offsetting

Given the concept of negative externalities, the concept of market-based mechanisms arises. Economists recommend the implementation of market-based mechanisms in order to create the economic incentives to affect the behavior of economic agents, address the environmental problems, and cope with the international agreements. These mechanisms operate by either putting a price on carbon emissions (cap-and-trade) or by allow for carbon emissions compensation elsewhere (offsets). These market-based incentives seek to make environmentally friendly technologies and/or operational changes financially more appealing, ultimately leading to the long-term aspirational goal of emissions reduction.

6.3.1 EU ETS

The EU Emissions Trading System (EU ETS) was established in 2005, has addressed emissions across various industries within the EU, including aviation since 2012. It was designed as a cap-and-trade system where the EU sets a limit to the total allowable emissions (cap) that is decreasing over time. These allowances can then be traded between companies, where companies with lower Marginal Abatement Costs (MAC) can invest in cleaner technologies and better operations to either minimize their own emissions or, potentially, profit by selling their surplus allowances to companies with higher MAC, as exemplified on the figure below. This market for allowances creates economic incentives for the companies to reduce their own emissions.

The EU ETS is mandatory for most of the economic activity, including the energy sector, industry and commercial aviation. Companies have enough allowances to cover their own CO_2 emissions, each allowance accounting for 1 tonne of CO_2, or purchase the excess allowances needed. The EU ETS is considered by many economists as the most efficient systems in place, ensuring a broader environmental impact. With this system it doesn't matter where the reductions are achieved. Emission reductions can be achieved in sectors with lower MACs, easier to decarbonize, and the sectors more difficult do decarbonize can buy allowances from others. Unlike offset programs, that allow for in-sector emissions as long as companies offset their emissions somewhere else, EU ETS guarantees real reductions. The EU ETS is an example of a market-based mechanism that puts in practice economic incentives to promote emission reductions and is the base of the EU climate action strategy (EU, 2014).

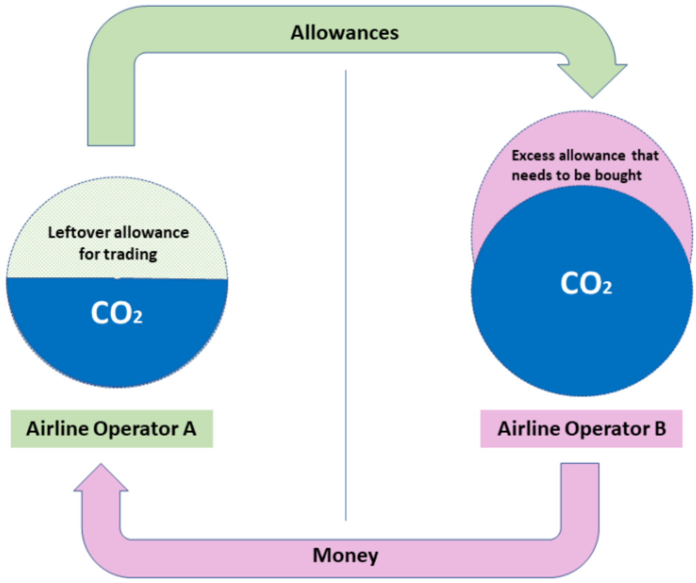

Figure 14: EU ETS cap-and-trade system. Source: EASA (2024)

6.3.2 CORSIA

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) was created in 2016 by the International Civil Aviation Organization (ICAO) as an instrument to reduce CO_2 emissions from commercial aviation. The ICAO member states had set ambitious goals regarding aviation, like a 2% annual improvement in fuel efficiency or a carbon-neutral growth from 2020 onwards. CORSIA is a complement to the in-sector efficiency gains, allowing for the offset of the emissions above the baseline. It worth to highlight that the baseline used is the 2019 emissions level, and not 2020, due to the drastic emissions level drop in 2020 caused by the COVID19 pandemic (ICAO, 2025).

CORSIA is a market-based mechanism where airlines are requested to offset emissions that exceed the baseline by purchasing carbon credits from eligible projects that reduce emissions or capture carbon somewhere else. This creates incentives for airlines to reduce their carbon footprint while contributing to the global emission reduction efforts. CORSIA is being implemented in three different phases, being currently on a voluntary phase, from 2021 to 2026. The mandatory phase will start from 2027 onwards, including all international commercial flights, with exception of few least developed countries and small islands. The phased implementation permits some flexibility and encourages wider adoption before the mandatory phase (ICAO, 2024).

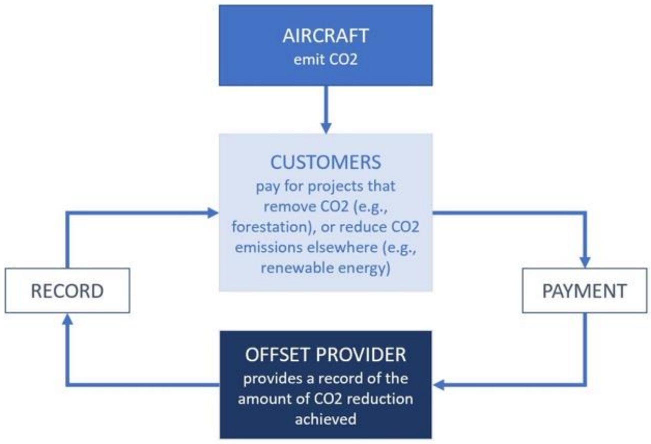

Figure 15: Carbon offsetting process. Source: IATA (2022)

6.4 The Voluntary Carbon Offsetting Market

Voluntary Market, on the other hand, operate outside the regulatory frameworks and participation is not mandatory. In this market, companies and individuals can buy carbon credits to offset their emissions as part of their corporate social responsibility or the personal commitment with reduction of the own carbon footprint. The voluntary market allows for the participation on a wide range of offset projects worldwide. These offset projects can be found in different sectors of the economic activity, such as reforestation, renewable energies or energy efficiency. Companies are often driven by shareholders demand, employers demand, clients demand or corporate social responsibility. The following figure describes the structure of the voluntary market for carbon offsets (EEX, 2024).

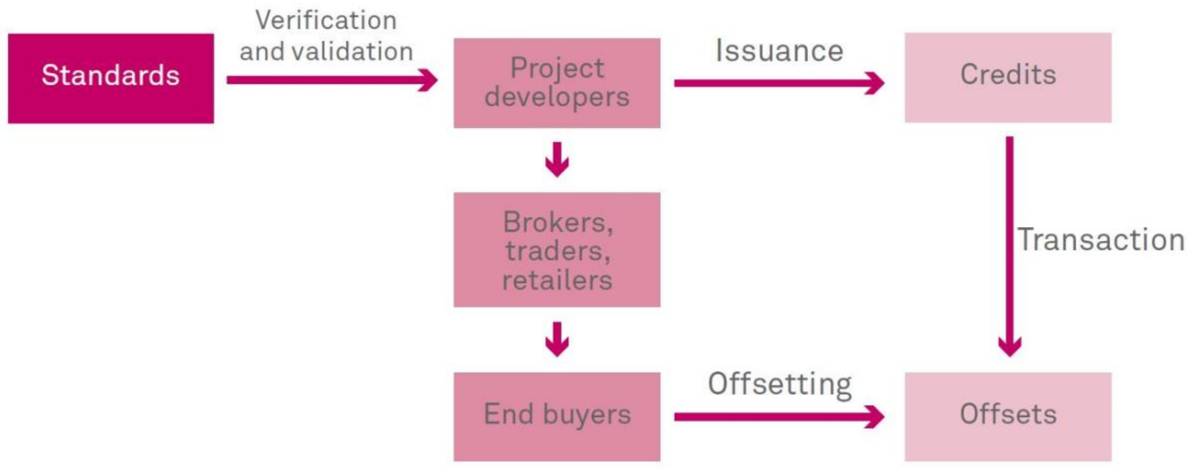

Figure 16: The structure of voluntary carbon markets. Source: S&P Global (2021)

6.5 Emerging Technologies for Offsetting: Direct Air Capture (DAC) and Carbon Capture and Storage (CCS)

Direct Air Capture (DAC) and Carbon Capture and Storage (CCS) are two innovative solutions that can help mitigating the negative effects of CO_2 emissions by directly removing carbon dioxide (CO_2) from the atmosphere to then be stored or used.

Direct Air Capture (DAC) is a technology that involves the removal of carbon dioxide (CO_2) from the atmosphere using different processes. This technology has the potential to address emissions from the sectors hard to decarbonize such as industry, shipping industry and aviation. DAC systems are normally composed by a set of big fans that forces the air to pass through chemical solvents or absorbent materials that captures the CO_2. The gas can then be concentrated and purified to be either stored under the ground or used in industrial processes like enhanced oil recovery or production of synthetic fuels, as described before (Climeworks, 2024).

Carbon Capture and Storage (CCS) involves the capture of CO_2 emissions directly from large sources like powerplants on industrial facilities before its even released into the atmosphere, and then storage underground where it will be locked ‘forever’. CCS can effectively capture

CO2 from his source, especially in sectors hard to decarbonize, allowing the use of fossil fuels without the harm of carbon emissions. The process involves the capture of CO_2, compression into a liquid state and then the transport, via pipelines, to adequate storage places, where its injected deep underground and safely stored and secured to prevent its release into the atmosphere (Global CCS Institute, 2022).

Both DAC and CCS have the potential to play important roles to achieve global climate goals by abating CO_2 emissions, even in sectors hard to decarbonize. But both technologies face huge challenges related to scalability, public acceptance and mainly the very high costs of the processes. Overcome this obstacle will require continued investments in R&D to escalate DAC and CCS. Also, the regulatory frameworks should incentivize the adoption of these technologies and reduce their costs. One report from the Energy Transitions Commission (ETC) highlights some actions required to scale up DAC and CCS, including the role of voluntary carbon markets and providing direct and indirect government support, ensuring the high credibility of carbon credits or building the necessary infrastructure, and supporting innovation via research and development funding (Energy Transitions Commission, 2022).

6.6 Evaluation of Market-based Mechanisms: Challenges and Improvements

For the scope of our work, we did a comparison between CORSIA and EU ETS. The main difference between the two mechanisms lies in the fact that CORSIA is a global market-based mechanism, whereas EU ETS is a regional mechanism only applicable to the flight from/to EU countries. Another important difference is that CORSIA covers only commercial aviation and EU ETS is applicable to all sectors of economy. Both mechanisms face problems to ensure integrity and in monitorization of the carbon emissions. There are several improvements that these mechanisms could include to guarantee a more accurate monitorization and reporting standards to ensure compliance. This could include the incorporation of new technologies, such as Blockchain and Artificial Intelligence (AI) to mitigate some problems faced and enhance transparency and efficiency of these mechanisms.

According ICAO, in order to be certified as an official offsetting projects for the aviation industry, project must provide proof that they actually:

1. Are additional.
2. Are based on a realistic and credible baseline.
3. Are quantified, monitored, reported, and verified.
4. Have a clear and transparent chain of custody.
5. Represent permanent emissions reductions.
6. Assess and mitigate against potential increase in emissions elsewhere.
7. Are only counted once towards a mitigation obligation.
8. Do no net harm.

(ICAO, 2019)

Carbon offsets have been subject to scrutiny and criticism raising concerns regarding some of the most important concepts, like for example:

Additionality: Could emissions reduction have occurred anyway?

Permanence: Does the offset have a long-term impact on the emissions reduction?

Leakage: Are the emissions shifting to other location or industry?

Ensuring the credibility and environmental integrity of carbon offset projects is crucial for their effectiveness in addressing climate change challenges.

In April 2024 the European Commission and EU consumer authorities started a legal action against 20 airlines for misleading greenwashing practices. The European Commission and the Consumer Protection Cooperation network, have identified several types of potentially misleading practices by 20 airlines, such as using the term Sustainable Aviation Fuel without justifying the environmental impact of the SAF; using the terms ‘green’, ‘sustainable’ or ‘responsible’ or use other implicit claims; claiming that the airline is moving towards net-zero without verifiable commitments and an independent monitoring system; or by creating the incorrect impression that by paying an additional fee to finance climate protection projects or supporting SAF the clients would fully counterbalance the CO_2 emissions (EC, 2024).

The following table, compiled by the author, permits an easy comparison between the two mechanisms, CORSIA and EU ETS in several dimensions. Here we can distinguish their goals, scope of action, the mechanism used, the implementation stage, main criticisms, the carbon-pricing structure and the advantages and disadvantages of each one of the systems. This comparison gives a clear perspective on how these mechanisms work and the main challenges they face.

Table 4: Comparison between CORSIA and EU ETS. Source: Summarized by the author from IATA (2022) and EU (2014)

	CORSIA	**EU ETS**
Goal	Achieve carbon-neutral growth in commercial aviation from 2020	Reduce greenhouse gas emissions in all sectors of the economy
Scope	Global, stablished by ICAO	European Union, Iceland, Norway, Switzerland and UK
Mechanism	Offset: Airlines are required to offset emissions above 2019 threshold by investing in projects that promote out-of-sector reductions	Cap-and-trade: Airlines are required to buy allowances for every tonne of CO_2 emitted. The total number of available allowances decreases over time, forcing emissions reduction
Status	On a voluntary phase. Mandatory phase starting in 2027	Applicable to aviation since 2012
Criticism	Aviation emissions can keep growing as long as they are compensated somewhere else	Increases airline costs. Regional application can create unfair competition
CO_2 Pricing	Variable, determined by the carbon offsets market	Variable, determined by the emission allowances market
Advantages	Addresses emissions indirectly, creating a demand for emission reduction projects in other sectors	Addresses emissions directly, generating a clear price signal for airlines. license revenues are used to finance decarbonization measures
Disadvantages	Does not regulate emissions directly, it depends on the effectiveness of compensation projects	It can significantly increase airline costs. As it only applies to a part of aviation, can create an uneven playfield or contribute to carbon leakage

7 Research methodology

In this chapter, the research methodology applied in this thesis is described, and the iterative process of data collection and analysis is explained in detail.

7.1 Case Study Approach

A case study is an empirical investigation that explores a contemporary phenomenon in depth and within its real-world context, particularly when the boundaries between the phenomenon and its context are not clearly defined (Robert K. Yin, 2015). Given the actual importance of Sustainable Aviation Fuels (SAF) in reducing carbon emissions for commercial aviation, SWISS International Airlines provides a valuable case study. The company's involvement with the adoption of SAF presents a contemporary, under-researched phenomenon making the case study methodology the most suitable approach to address the 'why' and 'how' of its implementation. This method was considered optimal by allowing the researcher to establish a logic sequence between the empirical data and the initial research questions, facilitating the ability to get meaningful conclusions from the subject studied (Robert K. Yin, 2015).

7.1.1 Qualitative research method

We selected a case study approach because it complements the qualitative and exploratory nature of our research on the implementation of Sustainable Aviation Fuels (SAF) by SWISS International Airlines. The investigation was conducted in two phases: data collection and data analysis, and both primary and secondary data sources were used. Primary data were gathered through an interview with the director responsible for SAF implementation at SWISS. Secondary data were collected from the Lufthansa Group Sustainability Report 2023, SWISS Environmental Report 2023, Lufthansa Group Financial Reports 2023, and an educational session on SAF presented by Jan Pechstein, Senior Director of Corporate Emissions Management & Sustainable Aviation Fuel at Lufthansa Group, along with official information retrieved from SWISS and Lufthansa websites.

The following figure illustrates the iterative nature of the research process, where we can identify the dynamic relationship between key stages: starting from the research question formulation, the research design, the data collection and analysis, and finally the reporting. The figure emphasizes the cyclical flow between data collection and data analysis, showing how data analysis can lead to refinements in earlier stages with the need for further data collection. This iterative approach allows for a continuous evaluation and refinement to ultimately provide rigorous and reliable research findings and conclusions (Busetto et al., 2020).

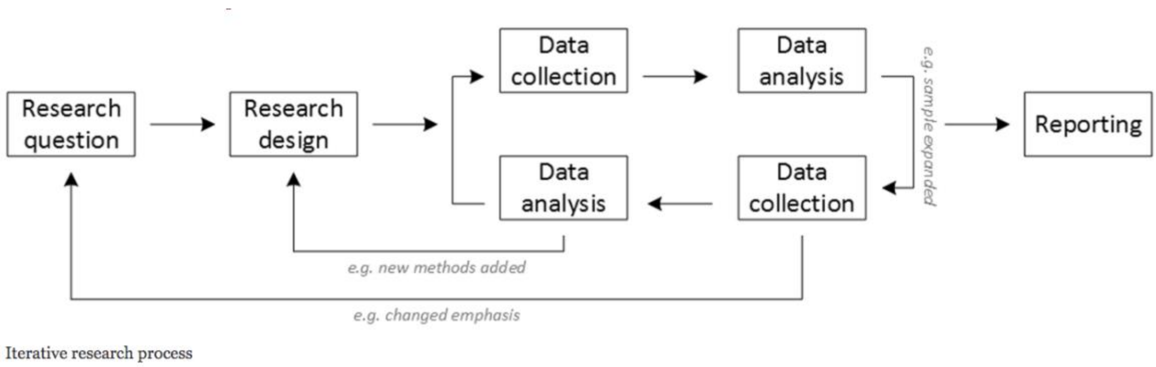

Figure 17: Iterative research process. Source: *Busetto et al. (2020)*

7.1.2 Semi-structured Interview

The primary source of data for this case study was a semi-structured interview conducted with the Head of Corporate Responsibility at SWISS. A semi-structured interview was chosen because allows for some flexibility, enabling the exploration of both predefined topics and emerging themes in greater depth. The interview format was chosen to allow open-ended responses, which provides high value qualitative insights into the implementation of Sustainable Aviation Fuels (SAF) by SWISS International Airlines.

During our literature review, we identified that while there are many studies dedicated to several aspects and details from SAF, there are little or even no studies dedicated to research how and why are large airlines integrating SAF into their operations. We also found that very little is known about the specific challenges and opportunities that airlines such as SWISS are facing in this context. This gap in the literature was the foundation for our choice of conducting a targeted interview to gather firsthand information from key personal directly involved in SAF implementation by SWISS.

Our interview was designed to explore several key aspects of SAF implementation by SWISS, including the company motivations, their strategic approach to SAF, operational challenges faced such as fuel availability and cost, regulatory compliance issues and the company's broader sustainability goals. The qualitative nature was considered essential to understand the technical aspects of SAF implementation but also the organizational and economic factors influencing its adoption. The insights from the interview were crucial for answering the initial research questions proposed and enhancing our understanding of SAF in the aviation industry.

With the selected research methodology in mind, we then directed our focus toward the research planning ensuring a contextualization between the data that should be collected through the semi-structured interview and the global landscape from international commercial aviation, where the company is included.

7.2 Research Design and Planning

SWISS International Airlines is the flag carrier of Switzerland and as subsidiary of the Lufthansa Group is also part of the Star Alliance, the world biggest airline network. SWISS was created in 2002 after the bankruptcy of Swissair. Its hub airport is Zurich but also have important operations in Geneva. SWISS has one of the most modern fleet in Europe, composed of approx. 90 airplanes, with a very low specific fuel consumption measured in liter per passenger kilometer (l/pkm). Nowadays SWISS is profitable, with 2004 showing a turnover of CHF5.6 billion and operating profit of CHF684 million. The company has approx. 10.000 employees and it is very important for the economy of Switzerland (SWISS, 2024a).

"The company has also set itself ambitious carbon targets, and plans to halve its 2019 net carbon dioxide emissions by 2030 and make its business and operations entirely carbon-neutral by 2050, particularly by promoting the use of sustainable aviation fuels" (SWISS, 2024b).

The main objective of this thesis is to study the application of Sustainable Aviation Fuels (SAF) within SWISS as a main strategy to achieve the environmental goals and cope with the regulations.

With this in mind, we invited Ms. Melanie Heiniger, Head of Corporate Responsibility at SWISS International Airlines for an interview.

7.3 Data collection

Primary data was collected through a semi-structured interview conducted with Melanie Heiniger, Head of Corporate Responsibility at SWISS, via ‘Teams’ on 21.10.2024, lasting approximately 50 minutes. The interview was then transcribed and prepared to enter the phase of data analysis. Ms. Heiniger position within the company was considered essential for this study. We considered that she could provide us with high value insights and information related to strategic and operational decisions as well as challenges faced by the company during SAF implementation.

Secondary data was gathered from the analysis of official public documents released by SWISS and the Lufthansa group. These included the annual environmental and financial reports, corporate press releases and the content from the official company websites. These documents provided context and operational insights that support triangulation, enhancing the validity of the findings derived from the interview.

7.4 Data Analysis

Following the methodology proposed by Robert K. Yin for data analysis in case studies, we enter into a systematic process of examining data and deriving key concepts, trends and relationships emerging from the empirical data collected beforehand. This analytical approach gave the student the tools to make sense of the data, infer theories, have a better understanding of the processes within the organization, derive findings and draw conclusions based on the evidence gathered from the data collected (Robert K. Yin, 2015).

7.5 Research Limitations

This study has some inherent limitations. First, by focus on only one airline, the generalization of the findings might not be possible. Although the case study of SWISS International Airlines may provide valuable insights on how the big airlines are coping with the legislation and the mounting pressure from corporations and individuals on the use of SAF, the results of this study may not be entirely representative of the universe of airlines, especially outside of Europe, where legislation is less strict. Second, this study is a ‘measurement’ of the state of the art at a point in time. SAF it's at the early stages of implementation and uncertainty is high. Regulation, technologies and market forces are changing constantly, and will evolve in the coming years, potentially impacting the long-term implications of the findings derived from this work. Future research could expand in this work by adopting a multi-case study and comparing how different companies are implementing SAF in their operations. Or, could opt by revisit SWISS at another point in time, this could offer insights into how the market forces, regulations or technology reshaped the SAF adoption over time.

7.6 Ethical Considerations

The author of this study works for SWISS International Airlines as a licensed aircraft engineer. This fact might have provided the author with valuable access to the experts and increased the depth of the case study. To reduce potential conflict of interests and mitigate potential bias, the following measures were implemented during and after the study:

Data Verification: Information collected from SWISS internal sources was cross-checked with external reports, grey literature, academic papers and data collected from the regulatory authorities.

Objective Analysis: During the entire process, the author maintained a critical approach, making an exercise of distinguishing between the factual data and what could be subjective interpretation, independent of the source.

Review: At the final stage of this work was asked specifically to the mentor of the student, Professor Isabel Moura, expert in economics and in sustainability, to perform a critical and independent review to prevent any bias or undesirable influence from the researcher affiliation with SWISS.

By addressing these ethical considerations, this study intends to be a valuable case study of the implementation of Sustainable Aviation Fuel (SAF) by SWISS, contributing for the gap found during the literature review.

8 Case Study - SWISS Implementation of SAF

This chapter explores how SWISS International Airlines is implementing Sustainable Aviation Fuels (SAF) as part of its decarbonization strategy. Drawing on primary data and institutional sources, the chapter analyzes corporate motivations, operational challenges, and the broader regulatory environment shaping SAF adoption.

8.1 Sustainable Aviation Fuels Adoption at SWISS

SWISS International Airlines is part of the Lufthansa Group and a member of the Star Alliance. The company aligns with the broader decarbonization strategy from the group and has also set itself very ambitious carbon targets, committed to halve its 2019 net CO_2 emissions by 2030 and become carbon-neutral by 2050. Aligning with the forecasts of ICAO and IATA, SWISS sees Sustainable Aviation Fuels (SAF) as the key element to achieve those goals. But the company is also committed with the other three pillars to achieve the mentioned goal, by investing in a state-of-the-art modern and efficient aircraft fleet, by implementing more sustainable operational procedures and by promoting high-quality climate protection projects to offset unavoidable emissions (SWISS, 2024b).

Why is SWISS implementing SAF?

SWISS is adopting SAF by a combination of regulatory, economic, and reputational incentives. European Airlines are facing increasing regulatory pressures (EU ETS, CORSIA, ReFuelEU Aviation Initiative), economic constraints (rising fuel costs, SAF pricing, carbon pricing), and increasing consumer awareness for sustainability. The strategy from the company reflects a proactive answer to those forces, ensuring a good early-stage positioning on a carbon-constrained economy and compliance with tightening regulations.

How is SWISS implementing the SAF?

SWISS strategy on SAF adoption assumes different levels. On a long-term perspective, the company is making direct offtake agreements, using the economies of scale that the group offers, but is also supporting innovative fuel technologies, like solar fuel - SWISS will be the first company in the world to use this new fuel (SWISS, 2022). On a daily basis, the company has involved the clients on the effort of SAF implementation, either through the green fare program (voluntary) or through the environmental cost surcharge (mandatory). SAF adoption remains uncertain mainly by its limited availability and high costs.

8.2 Environmental Benefits

Aligning with ICAO and IATA objectives, SWISS has set ambitious goals to halve 2019 CO_2 emissions by 2030 and achieve net-zero carbon emissions by 2050. SWISS has put in action strategies to cope with its environmental obligations while maintaining its operational efficiency and playing an important role on the economy of Switzerland and the World. The emissions reduction strategy implemented by SWISS was validated, in 2022 by an independent organization, the Science Based Target Initiative (SBTi) (SWISS, 2024d).

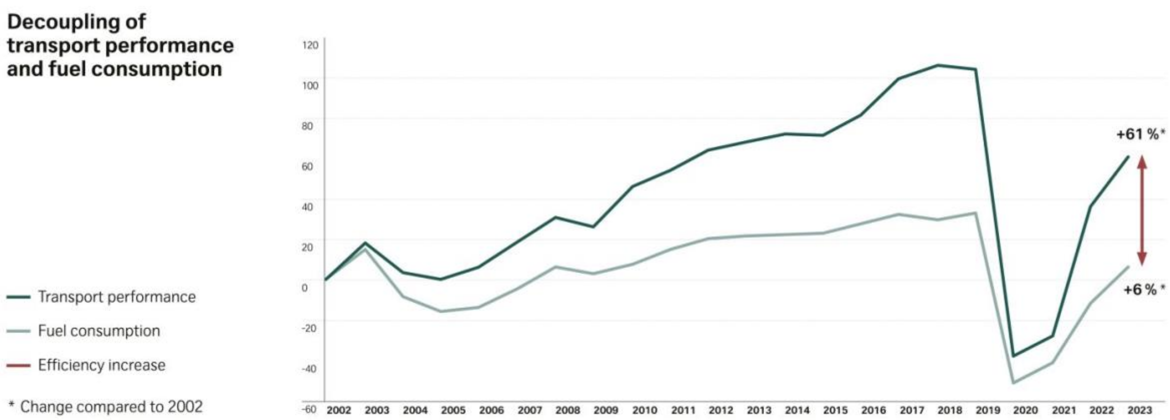

Figure 18: Decoupling of Transport Performance and Fuel Consumption. Source: SWISS (2023)

The graph illustrates how SWISS has achieved a decoupling between transport performance and fuel consumption since 2002, with a 61% increase in transport output (passenger-kilometers flown) compared to a much smaller 6% increase in fuel consumption - showing significant gains in operational efficiency.

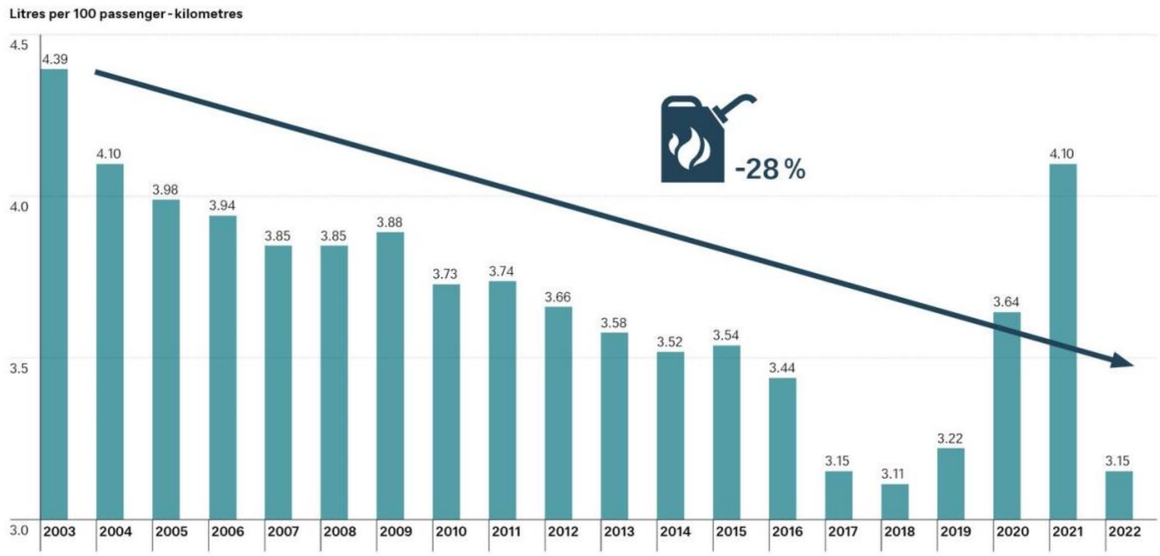

Figure 19: Evolution of the specific fuel consumption (l/100pkm) at SWISS. Source: SWISS (2023)

Another important measure of the environmental benefit achieved is the specific fuel consumption. By adopting technological advancements, fleet modernization and operational optimizations, SWISS was able to achieve a more efficient fuel use. The company has the lowest specific fuel consumption of the entire Lufthansa Group despite the increased demand for air travel. This achieving has a great contribution for reduction of emissions. The graph below shows the evolution of the specific fuel consumption over the years, showing a reduction of 28% in 20 years. It is evident outliers caused by the pandemic, when the aviation suffered a big impact, and load factors were extremely low. It is important to mention that despite these gains in efficiency, the total amount of fuel used has still grown, due to the increased demand for air travel.

To achieve further emission reductions, SWISS follows the International Civil Aviation Organization (ICAO) four-pillar strategy based on investments in technology (including fleet renewal), improved operational procedures, Sustainable Aviation Fuels (SAF), and investments in offset projects.

Fleet Renewal: SWISS is investing billions of CHF in new state-of-the-art aircraft to further improve the fuel efficiency and reduce CO_2 emissions. As referred before, the airline has the lowest specific fuel consumption of the entire Lufthansa Group, accounting for 3.27 liters per

100 passenger-kilometers (pkm). The consumption of modern airplanes is often compared to a small modern car.

Starting in 2025, SWISS is renewing its long-haul fleet with 10 Airbus A350-900 aircraft, the most advanced long-haul airplane in the world, designed for passenger comfort but also to further improve fuel efficiency and reduce environmental impact. According to Airbus, the A350-900 has a specific fuel consumption of around 2.5 liters per 100 passenger-kilometers and produces approximately 25% less CO_2 emissions when compared with the previous generation of aircraft. The A350 has also much less noise emissions that the previous models, another important consideration.

Operational Measures: SWISS also implements small operational improvements that collectively have a considerable impact on fuel consumption and carbon emissions. Dynamic rerouting, last minute refueling, single engine taxiing and engine washing are some examples of those measures. Engine washing, as an example, reduces fuel consumption around 1%, promotes better engine health and extends on-wing time.

Sustainable Aviation Fuels (SAF): Environmental benefits of SAF are undeniable as they can reduce lifecycle CO_2 emissions by up to 80%. The Lufthansa Group has achieved a collective reduction of over 43,600 tonnes of CO_2 emissions due to SAF use in 2023, with SWISS accounting for 5,400 tonnes of this reduction. SAF has the clear advantage of offering an immediate reduction in emissions, with no need for offsets, despite the price and its limited availability.

Collaborative Climate Projects: SWISS promotes the clients' engagement in climate protection initiatives as a mean to compensate for unavoidable emissions. The company also has some agreements with companies developing Carbon Capture and Storage technologies.

8.3 Economic Factors

The adoption of Sustainable Aviation Fuels presents a major economic challenge, as SAF is currently three to five time more expensive that conventional jet fuel. On an airline cost structure fuel represents the highest variable operational cost at about 25% of the total costs

(Doganis, 2019). With such a weight on the cost structure of the companies, SAF adoption becomes a big financial challenge.

To address this challenge, SWISS came up with some creative solutions. In 2023 the company introduced the green fare, where clients - either individuals or corporations - can, on a voluntary basis make a contribution to reduce the carbon footprint of their air travel. This fare offers different options, being the most common through the support with 20% of emissions being avoided through the use of SAF and the remaining 80% of the emissions being offset through climate-protection projects. In the first year 5% of the company's clients opted for the green fare (SWISS, 2023b).

To cope with the increased compliance costs imposed by newest European regulation, like EU ETS and ReFuelEU, the company announced that, starting from 2025, the fares will include an Environmental Cost Surcharge. This surcharge varies between CHF1 and CHF72 depending on the class and flight distance. (SWISS, 2024c)

8.4 Collaborations and Partnerships

Aware of the limited availability of SAF and the early stages of many of the technologies that will have to be used in the future to achieve the goals, SWISS and the Lufthansa group signed several important agreements relative to this subject, such as:

- **Offtake Agreements:** The Lufthansa Group has signed different agreements for 3.399 million liters of SAF for the entire group as a way to reduce risk of lack of supply.
- **Innovative Technologies:** SWISS signed a partnership with *Synhelion*, a startup dedicated to develop solar-based synthetic fuels, positioning the company as the first airline in the world to utilize sun-to-liquid fuels.
- **Carbon Capture:** SWISS has also established a cooperation with *Climeworks,* which is developing technologies of Direct Air Capture (DAC) to permanently sequester CO_2 or use it as a feedstock for synthetic fuels production.

These partnerships show that SWISS is committed in contributing to leverage these cutting-edge innovations to address the scarce availability, scalability and costs associated with SAF adoption.

8.5 Regulatory and Policy Factors

“Compliance related costs are increasing strongly in the next few years. The main cost driver will be the SAF blending mandate in EU, starting in 2025 with 2% and then increasing to 6% in 2030 and further. More additional costs will come from the various Emission Trading Systems (ETS)”.

“SWISS supports the establishment of global instruments and would welcome the introduction of a global SAF blending mandate. With the caveat that distortions of competition are minimized and carbon leakage is prevented, SWISS supports the introduction of the EU/CH SAF quota and the further development of the EU/CH ETS. SWISS considers the instrument of a mandatory blending quota as a suitable means to promote the use and production of SAF. In addition, decarbonizing air transport requires support programs, especially for the market introduction and scaling of SAF”.

8.6 Risks

The adoption of Sustainable Aviation Fuel (SAF) by SWISS International Airlines implies both opportunities and challenges. While SAF is seen as the key element to achieve the global ambition of reaching carbon neutrality for the sector. During our research we identified several important risks linked to its implementation. These risks should be taking into consideration either by the company and by the authorities responsible to design the regulatory landscape.

In this sub-chapter we explore the five risks identified during the research with higher potential to jeopardize the final goal. The discussion includes their potential impacts and possible mitigation strategies. Addressing these risks is considered essential to achieve meaningful environmental progress and avoid possible reputational damage.

8.6.1 Competitive Distortion

Aviation is one of the most competitive industries in the whole world. Companies compete in a liberalized market for clients, lowering margins and increasing aircraft load factors to remain profitable. SWISS and the other European airlines operate with a regulatory environment that is significantly stricter than that of many non-European regions. Europe is well known by having stricter environmental regulations than the rest of the world. The EU Emissions Trading System (EU ETS) and the ReFuelEU Aviation initiative, impose substantial costs on European airlines by requiring the possession of carbon allowances that cover emissions and setting SAF blending mandates. Even when the rest of commercial aviation is under the umbrella of CORSIA, we recall that CORSIA doesn't put a cap on carbon emissions, allowing for the emissions above the baseline to be offset. Companies based on regions with less strict environmental policies, like the Middle East, Asia or the USA can operate at lower operational costs.

Competitive distortion may be the final result of these disparities, with the risk of European airlines losing market share to non-European companies with lower compliance costs. European airlines may also consider relocating their hubs or rerouting some flights to reduce regulatory costs, which would result in negative environmental impact, harm the European economy and labor market and lead to another important risk discussed ahead, 'carbon leakage'.

To address competitive distortion some mitigation strategies may be putted in place, like:

Global regulatory harmonization: SWISS and the Lufthansa group advocate for a global international agreement under the ICAO that establishes uniform and universal carbon pricing mechanism and SAF mandates, as the only way to truly create a level playing field, making sure that all airlines are 'playing with the same rules' and facing similar environmental compliance costs.

European subsidies and incentives: Until universal regulation is not established, European Union could subsidies or tax incentives as a mean of offset the higher costs of SAF adoption and environmental compliance. Direct support to SAF could reduce the cost gap between SAF and conventional fuels and boost the European economy.

Collaborative initiatives: European airlines could cooperate and use economies of scale, making partnerships and offtake agreements as a way to reduce the risk either by the demand side, either by the supply side. SAF suppliers must have a guarantee of future demand to justify the vast investments needed in SAF production.

8.6.2 Carbon Leakage

Carbon leakage occurs when emission reduction policies in highly regulated regions drive airlines to shift their operations, routes, or fueling strategies to areas with less strict environmental rules. Thus, resulting in global emissions being transferred rather than reduced, compromising the effectiveness of regional climate policies.

Europe is particularly vulnerable to carbon leakage, as the costs imposed to the airlines, through EU ETS and ReFuelEU Aviation, are much higher when comparing with other regions such as Asia or Middle East, where mandates are minimal or null.

Regional regulatory disparities may give wrong economic incentives to European airlines, with possible negative outcomes. Airlines may reroute some of the long-haul flights through less regulated regions with cheaper jet fuel, increasing the total fuel used and carbon emissions. Or they could relocate maintenance, cargo or operational hubs outside of Europe with negative impact on emissions but also loss of economic activity and jobs within the EU.

Policymakers and aviation stakeholders must be aware of this risk and adopt strategies, like the ones described below, to prevent it and ensure effective emissions reduction, ensuring the viability of European airlines, like SWISS, and making sure that their sustainability efforts are making a positive contribution to genuine and global emissions reduction.

Global regulatory harmonization: Just like in the risk of competitive distortion, also carbon leakage can be mitigated by ensuring that the rules, and consequent compliance costs are universal, reducing the incentives to relocate operations to less-regulated regions.

Expansion of SAF credit mechanisms: Improving international cooperation through innovative solution like the ‘book-and-claim’ system would allow airlines to purchase SAF credits globally, making it more viable for them to comply with regulations.

Investment in SAF infrastructure at global Hubs: Promoting SAF production and availability at key international airports would ease its worldwide availability, minimizing the cost disparities that can result in carbon leakage.

8.6.3 Feedstock Competition

Another important risk to take into consideration is the risk of feedstock competition for SAF production. As discussed before, currently most of the production of SAF depends on sustainable feedstocks, such as waste oils, biomass or algae but the availability of this resources is limited and competes with other industries, such as renewable energy, agriculture or food production. This feedstock competition has some implications in terms of economic viability, scalability and sustainability of SAF.

Almost all SAF used nowadays are biofuels, which means that, as the demand rises the resource becomes scarcer and the price more volatile. Demand for used cooking oils, fats and crop-based biofuels is increasing in multiple sectors. Even if aviation is capable of paying a higher value for these feedstocks, the problem is only transferred to other sectors of economy. Another dimension of the problem is the competition with other agricultural goods for land, which could contribute to deforestation, biodiversity loss and food price inflation. As governments push for an increase of biofuels in road transport or power generation, that can introduce another layer of competition for feedstock. In case the demand outpaces a sustainable supply there is the risk of emerging illegal deforestation and unsustainable harvesting, which would undermine the environmental benefits of SAF and increase the reputational risk associated to airlines.

Mitigating the risk of feedstock competition requires action from airlines, governments and other stockholders, like SAF producers. We identified some of the possible mitigating strategies.

Investment in next-generation SAF technologies: Investing in other SAF production methods like algae-based biofuels or non-biomass sources, such as synthetic fuels derived from hydrogen such as the Power-to-Liquid, Sun-to-Liquid and through the application of DAC technologies.

Regulatory safeguards: Ensuring the compliance with sustainable regulatory certification such as the EU Renewable Energy Directive (RED II) criteria to make sure that SAF feedstocks do not contribute to deforestation, illegal practices, food shortages, or unethical labor practices.

Circular economy approaches: Further enhance the so-called waste-to-fuel technologies to maximize the use of resources, reducing dependence on agricultural feedstocks, and ensuring that low-value resources such as used oils, forestry residues, MSW or industrial waste gases can be effectively converted in a high-value SAF.

8.6.4 Oil Price Volatility

The fossil fuel price volatility poses a major risk for SAF adoption. If crude oil price has a significative decrease, the cost gap between SAF and fossil fuel widens, making SAF less appealing to airlines, operating on tight profit margins. Historically the periods of low oil prices resulted in a lower interest and lower investments in alternative fuels or more advanced technologies, as the investors give priority to cost efficiency instead of sustainable practices.

The oil market is volatile, complex and closely linked to global economic and geopolitical events. Events like OPEC+ decisions, regional conflicts or global recessions can have sudden effects on oil prices. In the event of a prolonged decline in oil prices, SAF adoption would become even more challenging. For example, given current political and economic tendencies, it is expected that the USA and Argentina will increase their oil production in the coming years, especially under leadership favoring deregulation and expanded fossil fuel extraction.

Another important fact to consider is that, as the road transport sector electrifies, the demand for oil can drop in such a way that could lead to a drop in prices. If fossil-fuel prices become excessively volatile, airlines may hesitate to commit to long-term SAF offtake agreements. Airlines typically rely on fuel hedging strategy to cope with uncertainty and make their financial planning, unpredictable oil price movements can remove the incentive to invest in SAF adoption unless there are strong regulations.

To mitigate the risk of oil price volatility during SAF adoption the following measures were identified:

Stable regulatory frameworks: The regulations should be global, predictable and stable to protect SAF adoption from market-driven oil price fluctuations.

Financial incentives: Further extending EU ETS support scheme that is being used to support the price differential between the use of fossil kerosene and the Sustainable Aviation Fuel, through the reserve of 20 million carbon allowances. This could also assume the shape of a coordinated effort between ICAO and EU to establish a global SAF price stabilization mechanism.

Corporate and consumer engagement: The example of SWISS is a good example of how airlines can engage corporate or private clients into the sustainable practices, through voluntary green fares or environmental surcharges, reducing the risk and increasing the predictability.

These measures can contribute for a reduction of exposure to oil price volatility risk, ensuring that SAF adoption is still financially viable when conventional fuel prices are low.

8.6.5 Greenwashing

Greenwashing is the risk of airlines claiming environmental benefits that are not real. Transparency and credibility are key concepts regarding this risk. As airlines promote their sustainability efforts, it is essential that these benefits are transparently reported and rigorously verified, to avoid being perceived by clients and general public as misleading, potentially undermining the consumer trust and weakening the long-term decarbonization strategy.

Sustainability claims are not subject to a universal certification system and many times lacks the implementation of the verification process. SAF can reduce lifecycle CO_2 emissions up to 80% when compared with conventional fuel, but these reductions are dependent on the feedstock, production method, and supply chain. Some fuel producers may advertise for the maximum reduction without counting for indirect or induced emissions. The lack of transparency may lead the consumers to question the airline sustainability claims and reduce its willingness to participate in voluntary SAF programs (e.g., green fares) with potential reputational risk for airlines. Also, some airlines may use SAF as a marketing tool rather than an effective decarbonization strategy, if that happens it may be perceived as greenwashing.

Greenwashing is one of the most important risks, because it comes always associated with reputational damage, and reputation is of crucial importance for airlines. To avoid the risk of being perceived as greenwashing, the airlines should adopt, among others, the following measures:

Adoption of independent certification standards: Airlines should commit to use SAF that meets internationally recognized certification systems. These certifications ensure that feedstocks are from sustainable sources and emissions reductions are accurate. Linked to this, the authorities should promote independent audits and compliance checks.

Lifecycle Emissions Accounting: SAF providers and airlines should implement full life-cycle analysis (LCA) methodologies to ensure that carbon savings are accurately measured from feedstock sourcing to combustion. This includes direct, indirect and induced emissions.

Clear and honest communication: Airlines should ensure that the communication with the clients and investors provide realistic claims regarding SAF status and limitations to avoid unrealistic claims.

The challenges are huge, but SWISS has the possibility to be ahead on sustainable practices, in the European and World landscape, by addressing these risks and taking action to avoid them. Being part of one large European group, SWISS has the opportunity to use its scale to:

- Advocate for Global regulatory harmonization.
- Advocate for better SAF certification standards to improve market transparency.
- Expand its ‘green fare’ program with clear, verifiable metrics for emission reductions.
- Work with the regulators to establish SAF reporting best practices that can be used as a model for other industries.

By committing to these initiatives, SWISS can ensure that its efforts toward a more sustainable future for aviation are perceived as genuine and impactful, and that they align with the long-term aspirational goal of being carbon neutral by 2050.

9 Results

In this chapter we interpret and contextualize the findings related to the adoption of Sustainable Aviation Fuels (SAF) by SWISS International Airlines within the context of aviation sustainability, the regulatory environment and the market dynamics. The discussion addresses the implications of SWISS strategies on a point of view of the economic performance and environmental outcomes, but also the challenges arising from the inherent risks and regulatory uncertainty.

9.1 Interpreting the Drivers and Implementation Strategies

SWISS's adoption of Sustainable Aviation Fuels (SAF) is primarily driven by regulatory pressures, economic considerations, and reputational incentives. The proactive approach is reflection of a strategic answer to strict European policies – such as CH/EU ETS and ReFuelEU Aviation Initiative – which imposes a cap on carbon emissions with consequent direct and indirect costs on carbon-intensive operations. These regulatory forces are complemented by a rising consumer demand for sustainable travel options and rising fossil fuel costs. By integrating SAF in its operations, SWISS ensures regulatory compliance but also positions itself as a market leader in sustainable practices in aviation.

The implementation of SAF by SWISS is a complex and multifaceted process. The airline leverages the positioning inside the Lufthansa group to participate in direct SAF offtake agreements, signed partnerships with innovative fuel producers (*Synhelion*) and engages in voluntary market mechanisms, with the introduction of the 'green fare'. With this approach, SWISS intends to address the current limitation of SAF availability and mitigates future supply risks. Also, by involving the customers with the voluntary market for sustainable practices, the airline makes a connection between client engagement and sustainable outcomes, sharing responsibility and enhancing transparency during the decarbonization process.

9.2 Environmental and Economic Implications

On an environmental perspective, SAF is the main component of the decarbonization strategy. The airline's ambitious goals – to halve their CO_2 emissions by 2030 and ultimately reach net-zero emissions by 2050 – are backed by the implementation of SAF, investments in fleet renewal, more efficient operational procedures, and participation in climate-protection projects. As discussed, SAF have the potential to reduce lifecycle CO_2 emissions by up to 80% (depending on the production method) can be used as a direct replacement for fossil fuels, without any modification on aircraft or engines (drop-in ready) offering immediate environmental benefit. These benefits can be amplified by an integrated strategy, where technological advancements and operational efficiency are in a synergy.

On an economic perspective, the high cost of SAF—three to five times the cost of conventional jet fuel—is the main challenge. Fuel price is the main portion of the airline's operational costs, and the premium price of SAF introduces additional financial pressure to the tight profit margins. SWISS has addressed this challenge by encouraging the customers to participate on the effort, either on a voluntary basis (with the introduction of the green fare in 2022), either through the Environmental Cost Surcharge introduced in January of 2025 to transparently share the compliance-related costs. These measures are examples of economic solutions designed to balance regulatory compliance and financial viability.

9.3 Collaborative Initiatives and Policy Implications

SWISS collaborative initiatives are crucial to the company decarbonization plan. By cooperating with the Lufthansa group, the airline increases the negotiation power to secure a long-term stable supply of SAF. SWISS also fosters technological innovations such as solar-fuel (*Synhelion*) or Direct Air Capture (*Climeworks*). Engaging in these strategic alliances allows the company to increase its resilience against future supply-chain uncertainties and mitigate technological risk while serving as a benchmark for the industry collaboration.

The regulatory environment remains uncertain. On one perspective, the higher carbon emissions prices associated with increasing mandates are drivers for SAF adoption. On the other hand, they contribute to cost disparities that increases the risk of competitive distortion and carbon leakage or even economic viability of the operators. SWISS advocates for a global regulatory harmonization. That, together with robust support mechanisms, would contribute to level the playing field ensuring that the environmental progress is achieved without disadvantaging the European airlines relative to their global competitors.

9.4 Addressing the Risks

Our study has identified several risks, described below, linked to adoption of SAF. Each risk poses a challenge.

Competitive Distortion and Carbon Leakage: Higher regulation-compliance costs within Europe can incentivize the European airlines to shift their operations to less regulated regions, undermining the global emissions-reduction efforts and harm the economy of the region. This discussion emphasizes the importance of a global regulatory framework to prevent this risk.

Feedstock Competition: The limited availability of sustainable feedstocks creates a competitive environment that can drive costs up or contribute to illegal or unsustainable practices. Feedstock diversification and a strong investment in next-generation, non-biogenic, SAF technologies are key to mitigate this risk.

Oil Price Volatility: Fossil fuel price fluctuations may have an impact on SAF attractiveness, especially as other sectors move towards electrification and the demand for oil becomes uncertain. Stable global regulations and the correct economic incentives are an important layer of protection against market uncertainties.

Greenwashing: Airlines may face the risk of its SAF implementation initiatives being perceived as superficial or marketing moves, without clear standardized verification processes and transparent reporting. Using new technologies can help the implementation of rigorous certification standards that account for lifecycle emissions to maintain credibility and increase consumer trust.

Our discussion suggests that addressing these risks requires an adequate response from both the regulators and the airlines. To make sure that SAF adoption is translated in genuine environmental benefit while keeping economic and financial viability, SWISS must commit to clear and transparent communication, keeping investing in innovative technologies and making strategic partnerships with SAF producers.

9.5 Implications for Theory and Practice

By examining the real-world implementation of SAF through a case study of SWISS International airlines, this study offers valuable insights that bridges the gap between economic theory and practical application, in the field of sustainable aviation.

From a theoretical perspective, the case shows the relevance of classical economic concepts such as negative externalities, Pigouvian pricing, or induced innovation, and the importance that regulation has to provide the incentives to influence corporate behavior on the decarbonization effort. The study also shows how reputational drivers and voluntary market can coexist with mandatory market and market-based instruments, within the firm's strategy.

From a practical point of view, the study offers insights into how airlines can incorporate SAF into their operations despite its current economic and logistical barriers. The case of SWISS illustrates strategies such as cost-sharing with customers (via green fares and environmental surcharges), participation in the voluntary market, and partnership with SAF producers or innovative technological development. All this can serve as a model of best practices to adopt by other airlines with similar challenges. The study also shows the importance of coordinated international regulation as a way to level the playing field, reduce market distortion, and guarantee long-term investment certainty.

10 Conclusion

This thesis was dedicated to analyzing the implementation of Sustainable Aviation Fuel (SAF) by SWISS International Airlines, as part of its broader decarbonization plan of action. Being a qualitative study, we opted for a case study approach, based on data retrieved from an interview with an expert in corporate responsibility and extensive review of the corporate and institutional reports.

10.1 Summary of Research Findings

Implementation strategies: SWISS has leveraged being part of the Lufthansa group in integrating SAF. The process involves a multi-dimensional approach, with direct procurement, strategic collaboration with innovative fuel producers (*e.g., Synhelion*), and consumer engagement with voluntary mechanisms, like the 'green fares'.

Environmental benefits: SAF offers significant lifecycle CO_2 reductions, as previously discussed. In 2023, SWISS accomplished an emission reduction of approximately 5.400 tonnes, making a positive contribution to the total CO_2 reduction of 43.000 tonnes achieved by the Lufthansa Group.

Economic challenges: The adoption of SAF presents significant economic barriers. The most significant challenge is the price. With costs of production between three to five times higher than conventional jet fuel. SWISS has adopted some strategies to deal with this challenge, partially addressing the cost gap through cost-sharing mechanisms like the 'green fares' introduced in 2023 and the Environmental Cost Surcharge introduced in 2025.

Regulatory and market forces: The drivers for SAF implementation are not only regulatory frameworks – such as CORSIA, CH/EU ETS and ReFuelEU aviation – but also a growing consumer awareness and the resulting increase in demand for more sustainable air travel.

Risks and constraints: Among the most significant risks concerning SAF adoption are limited feedstock availability, the risk of competitive distortion between regions, and potential carbon leakage. Future globally harmonized regulation and greater investment in next-generation SAF technologies are some of the most relevant means to mitigate these risks.

10.2 Practical and Policy Implications

As shown by the findings of our case study, there is a delicate balance between environmental ambition and the economic viability of the airlines. To manage this balance, airlines can adopt several strategies to integrate SAF smoothly into their operations, such as innovative procurement strategies, collaborative partnerships, transparent communication with stakeholders, and client involvement.

For policymakers, this case shows the importance of globally harmonized regulations and well-designed financial incentives. The existing market structures and regulatory loopholes may generate perverse incentives, encouraging airlines to prioritize lower-cost offsetting rather than investing in structurally cleaner technologies like SAF. Stable carbon pricing mechanisms, SAF mandates, and incentives for technological development are essential to scale up SAF production and bridge the cost gap with fossil fuels.

There is a cost-benefit asymmetry in the economics of decarbonization that can lead to the practice of free-riding. Because decarbonization costs are high and local and the benefits are diffused and distant in space and time. This might give strong incentives for free-riding, where countries and companies delay actions, hoping for the others to lead. This behavior distorts rational cost-benefit analysis, reinforcing the need for globally harmonized regulation and credible long-term policy commitments.

10.3 Academic and Practical Contributions

As discussed in section 9.5, the findings of this study offer a relevant contribution to both academic research and industry practice in the fields of aviation and sustainability. By analyzing the implementation of SAF by SWISS through a case study, this research bridges a gap between theory and real-world application.

From an academic perspective, this study expands on the literature on sustainability in aviation, particularly in the context of incentives. It illustrates how economic theory can be observed in practical decisions made by aviation managers and other industry stakeholders. It also provides a grounded, empirical perspective that complements the quantitative techno-economic analysis with qualitative data drawn from actual corporate practice.

From a practical perspective, the research identifies instruments that airlines can adopt into their strategies to integrate SAF into operations, such as customer participation mechanisms, partnership with SAF producers, and use of book-and-claim systems. These strategies, derived from the SWISS case, can provide valuable data to other airlines, fuel producers, and policymakers. The findings also highlight the need for international regulatory alignment to create a leveled playing field and allow long-term investments in SAF, needed to escalate supply that can meet the demand.

These contributions offer a deeper understanding of how SAF can be the key to decarbonize aviation without compromising economic viability.

10.4 Answering the Research Questions

This section revisits the research questions presented in Chapter 1 and summarizes how they have been addressed based on the findings of this study. The answers below are grounded in the empirical analysis and theoretical discussion developed during the thesis.

Q1: Can Sustainable Aviation Fuels (SAF) support the aviation industry's goal of net-zero carbon emissions by 2050 while contributing to global economic development and maintaining airline economic viability?

Our research shows that, despite the logistic challenges and the high costs, SAF plays and will continue to play an essential role on the aviation decarbonization trajectory. With the correct incentives and clear regulations, the progressive adoption of SAF, has potential to enable carbon-neutral aviation operations without compromising the economic viability of airlines.

Q2: Why and how is SWISS International Airlines implementing SAF in its operations?

SWISS is adopting SAF by a combination of regulatory, economic, and reputational incentives. The airline has put in action a series of different strategies to address the high cost of SAF, such as the participation of clients, either on a voluntary or mandatory basis, with “green fares” and “Environmental Cost Surcharge”. These mechanisms reflect the effort to internalize environmental costs to achieve sustainability goals.

10.5 Final Thoughts

Aviation is one of the most difficult industries to decarbonize for techno-economic reasons. To achieve the goal of net-zero carbon emissions by 2050 proposed by ICAO, Sustainable Aviation Fuels (SAF) are a key element. The case study of SWISS International Airlines demonstrates that essential steps are already being taken, and SAF — once a distant concept or an experimental solution — is now being implemented by major airlines like SWISS, proving that change is not only possible, but is happening.

Often, we tend to imagine the future as a larger version of the past. However, the future of humankind is not shaped by repetition, but by reinvention. History gives us reason for optimism. Time and again, humanity has been capable of solving the biggest problems it has faced, driving progress with creativity, innovation, and cooperation. This moment is no different. With effective incentives, sustained effort, progressive thinking, and technological advancement, aviation can make a significant contribution to a more sustainable future.

11 Study Limitations and Directions for Future Research

This section presents the most relevant limitations of this research and suggests possible directions for future research. This empirical study provided us with valuable insights from real world implementation of Sustainable Aviation Fuels (SAF) by SWISS International Airlines, but some limitations need to be acknowledged. These limitations are intrinsic to the research method, the data collection process, and the scope of the case study approach.

11.1 Limitations of the Research

Generalizability: This study focuses on only one airline, SWISS International Airlines, a large European company, part of the Lufthansa Group, one of the largest airline groups in the world. This might be a limitation, as the findings might not be applicable to smaller airlines or to airlines operating outside of the highly regulated European market.

Data Source: The research relies on data gathered from a single interview with the director responsible for corporate sustainability, combined with financial reports and sustainability reports published by the company. While this source provides a valuable internal perspective, it introduces the possibility of reporting bias or selective disclosure.

Market Volatility: The SAF market is in continuously evolving. By being relatively recent and being influenced by external factors such as oil price fluctuations, geopolitical changes, regulatory shifts, or technological development, the long-term viability and adoption of SAF may be affected by these dynamics.

11.2 Directions for Future Research

Given the limitations discussed in the previous section, there is potential for future research in this field by exploring one or more of the following topics.

Comparative Study: Future research could adopt a multi case study approach and compare how different companies are implementing SAF, especially those operating in a different region (USA, Middle East, Asia) with different regulatory landscape. This would offer a broader understanding of SAF adoption under different market conditions.

Cost-Benefit Analysis: Future research could use quantitative data to assess the long-term economic impacts of SAF implementation. This may include the cost savings related to carbon pricing mechanisms, future fuel price projections, and/or potential changes in fare prices due to SAF adoption.

Consumer Behavior: Studies could look into the demand side of the equation. It would be interesting to examine the price elasticity of demand for SAF, studying the passenger's willingness to pay a premium for lower-emission flights. This dimension could be explored through surveys or behavioral economics tools.

Emerging Technologies: Future research could assess the viability of next-generation sustainable fuels. The study could provide data relative to the long-term potential and scalability of alternative solutions beyond the current SAF options, such as hydrogen-based synthetic fuels, solar fuels, or other innovative energy sources.

Acknowledging these limitations is essential for a more grounded interpretation of the findings, while our proposals research directions may guide future studies in this subject, contributing to a broader and deeper understanding of SAF's potential to fuel aviation decarbonization, supporting progress toward a more sustainable future.

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Appendix - Interview

SAF Adoption at SWISS International Airlines

1. **Integration into Operations: How is SWISS currently utilizing SAF in its operations? Are there specific routes or flights where SAF is being prioritized?**

SWISS actively supports the development and use of SAF. Since 2019, we have continuously expanded SAF our products for private and business customers. In 2021, SWISS became the first commercial airline to use SAF for operations from Switzerland.

SAF is fueled through the existing fuelling infrastructure established by LHG at various airports (especially FRA). There is no regular fueling in Switzerland and thus no specific flights or aircraft that are fueled with SAF. When we procure SAF as SWISS or LHG, ecological and economic criteria are decisive for us and not the location of fueling (because CO_2 savings have a global impact). Short transport routes are essential to avoid unnecessary CO_2 emissions and costs.

2. **Environmental Benefits: What are the environmental advantages of using SAF compared to conventional aviation fuels? Can you provide data on the reduction in carbon emissions achieved through SAF?**

The environmental advantages of using Sustainable Aviation Fuels (SAF) compared to conventional aviation fuels include:

- Reduction of carbon footprint by at least 80% over the entire lifecycle.
- Emission of fewer particles during combustion.
- SAF can be used in existing aircraft and fueling infrastructure, making it a practical alternative.
- SAF helps in directly reducing emissions rather than relying on emission offsetting.

These benefits make SAF a crucial component in the decarbonization of aviation. SWISS has reduced approx.. 5’400t of CO_2 through the use of SAF in 2023 (LHG reduced ofer 43’000t of CO_2).

3. **Challenges and Strategies: What are the key challenges SWISS faces in adopting and scaling up the use of SAF? What strategies is the company implementing to overcome these challenges?**

The main challenges include high production costs (SAF is 3-5 times more expensive than conventional kerosene), limited availability, and the need for technological advancements. To overcome these, SWISS is investing in research and pilot projects, forming strategic alliances, and developing targeted SAF offerings for private and business customers. These efforts aim to accelerate market development and increase SAF production.

4. Collaborations and Partnerships: Is SWISS working with other airlines, fuel producers, or governments to increase SAF availability and usage? Could you provide examples of such collaborations?

SWISS is working with the Lufthansa Group, its partners and customers to promote the development and availability of SAF through targeted measures and collaborations. LHG is working with different fuel suppliers to secure long-term availability of SAF.

In view of the limited availability of biofuels, SWISS is promoting the development of solar fuels, and established a strategic collaboration with Synhelion, a pioneer in the sustainable solar fuel field, at the beginning of 2022. The aim of the partnership is to accelerate the market launch and scale-up of this forward-looking technology. The partnership marks a significant milestone in sustainable aviation, with Synhelion's first demonstration solar fuel production plant inaugurated in June 2024. SWISS will be the first airline worldwide to use solar fuels.

5. Future Objectives: What are SWISS's long-term objectives for SAF usage? How does the company plan to increase the proportion of SAF in its overall fuel consumption?

SWISS has set itself ambitions CO_2 reduction targets. We want to achieve net zero CO_2 emissions by 2050. On the way there, we want to halve our 2019 net CO_2 emissions by 2030. The main levers supporting these targets are the use of modern aircraft, the continuous optimisation of flight operations, the use of Sustainable Aviation Fuels, and additional investments in climate protection projects. The key to achieving the CO_2 targets for aviation lies in the use of Sustainable Aviation Fuels (SAFs). Starting in 2025, the EU implements a SAF mandate, starting at 2% SAF that has to be blended when fueling in Europe. This mandate will increase to 6% in 2030 and much higher afterwards.

SWISS is working with the Lufthansa Group, its partners and customers to promote the development and availability of SAF through targeted measures and collaborations. We are continuously expanding our "Sustainable Choices" for our private and corporate customers to make their air travel more sustainable through the use of SAF (e.g. Green Fare).

6. Economic Factors: How does the cost of SAF compare with traditional aviation fuels? What measures is SWISS taking to manage the economic impact of SAF adoption?

The cost of SAF is currently three to five times higher than conventional aviation fuels. To manage the economic impact, SWISS is investing in targeted measures and collaborations to advance the development and availability of SAF, alongside the Lufthansa Group, partners, and customers. We are also involving our customers and continuously expanding our "Sustainable Choices" to make air travel more sustainable through the use of SAF (e.g. Green Fare). SWISS and LHG have also introduced an environmental cost surcharge to cover part of the strongly increasing compliance costs (SAF mandate, ETS, etc.).

7. **Regulatory and Policy Landscape: How do current regulations and policies affect SWISS's use of SAF? What changes in the regulatory framework would SWISS like to see to facilitate greater SAF adoption?**

Compliance related costs are increasing strongly in the next few years. The main cost driver will be the SAF blending mandate in EU, starting in 2025 with 2% and then increasing to 6% in 2030 and further. More additional costs will come from the various Emission Trading Systems (ETS).

SWISS supports the establishment of global instruments and would welcome the introduction of a global SAF blending mandate. With the caveat that distortions of competition are minimized and carbon leakage is prevented, SWISS supports the introduction of the EU and CH SAF quota and the further development of the EU/CH ETS. SWISS considers the instrument of a mandatory blending quota as a suitable means to promote the use and production of SAF. In addition, decarbonizing air transport requires support programs, especially for the market introduction and scaling of SAF.

8. **Corporate Responsibility and Customer Relations: How does SWISS's investment in SAF and sustainability initiatives align with its broader corporate responsibility goals and customer expectations?**

Our commitment to more sustainable air transport is a central pillar of our corporate strategy. SWISS creates social, societal and economic value through its business model.

SWISS pursues three priorities as part of its sustainability agenda:

- Emissions management: holistic reduction of our ecological footprint.
- Technology development: promoting the scaling and market entry of climate protection technologies (e.g. SAF).
- Social commitment: responsibility as an employer and company.

SWISS's investment in SAF thus aligns perfectly with its broader corporate responsibility goals. We also experience an increasing awareness of our customers to our "Sustainable Choices" offers and we are continuously expanding our product portfolio to promote more sustainable flying.

9. **Measuring Impact: How does SWISS evaluate the success of its SAF initiatives? What metrics or benchmarks are used to measure progress and impact?**

We have established comprehensive dashboards and reports to measure the success of our SAF initiatives and our offers for more sustainable flying. We calculate the amount of SAF and CO_2 emission reduction that could be achieved through these initiatives.