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Assessment of CO2 emissions and cost-benefit analysis of medium-range commercial aircraft powered by Sustainable Aviation Fuel

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Abstract

Within the wider context of climate change and global decarbonization goals, the aviation sector is a significant source of various greenhouse gases and air pollutants. Aircraft engines emit not only carbon dioxide (CO_2), the main responsible for global warming, but also nitrogen oxides (NOx), sulphur oxides (SOx), unburned hydrocarbons, carbon monoxide (CO), particulate matter and water vapor. These emissions contribute not only to climate change but also to local air quality degradation, especially around airports. As the number of flights is expected to increase significantly by 2050, the need to reduce aviation's polluting gas emissions becomes even more urgent. While Sustainable Aviation Fuels (SAF) represent one of the most promising options, other complementary solutions are also under development. These include improvements in engine efficiency, the design of lighter and more aerodynamic aircraft, optimized flight operations, and emerging technologies such as hydrogen propulsion and electric aircraft. Among all the possibilities, this thesis presents a comprehensive analysis of the strategic potential of Sustainable Aviation Fuels for reducing greenhouse gas emissions across the aviation sector, evaluating the life cycle environmental impacts and economic implications of SAF adoption, considering various production pathways and feedstock types. The analysis focuses on medium-range commercial routes and includes a comparative evaluation of SAF blends across five major international airports representing different operational and geographic conditions, highlighting how corporate strategies, feedstock availability, and production technologies influence emissions reductions and cost-effectiveness. The study shows that, as the blend of SAF in the fuel mix rises, emissions drop noticeably, but, sustainable fuels currently being more expensive than conventional jet fuel, this reduction comes with higher cost. This highlights both the critical role of SAF in meeting climate goals and the economic challenges that must be addressed to support its widespread adoption. The eventual purpose is to provide actionable insights for policymakers and industry stakeholders aiming to optimize SAF integration in the medium-haul segment, balancing sustainability objectives with operational and financial feasibility.

Summary

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Introduction

Environmental issues such as climate change, air pollution, and resource depletion are among some of the most critical challenges humanity is facing today. The global community recognises the urgent need to reduce greenhouse gas (GHG) emissions and transition towards more sustainable practices across all sectors. According to the Intergovernmental Panel on Climate Change (IPCC), limiting global warming to 1.5°C above pre-industrial levels requires rapid and far-reaching transitions in energy, transport, and industry.

Efforts to mitigate environmental impacts have been multifaceted, including improvements in energy efficiency, the adoption of cleaner technologies, and the development of alternative fuels. International agreements such as the Paris Agreement have catalysed coordinated action, with countries committing to reduce emissions and promote sustainable development. Innovations in renewable energy, electrification of transport, and carbon offsetting schemes are among the strategies being explored and implemented.

While significant progress has been made in sectors like road transport and energy production, aviation presents unique challenges due to its reliance on high-energy-density fuels and the complexity of global operations. As such, the sector is actively pursuing a variety of solutions, from operational improvements and new aircraft designs to Sustainable Aviation Fuels and emerging propulsion technologies. Understanding the broader environmental context and the scale of global air traffic is essential to appreciate the scope and urgency of these efforts.

For these reasons, it is crucial to evaluate all potential alternatives to conventional jet fuel. This thesis focuses specifically on the use of Sustainable Aviation Fuels as a replacement for traditional kerosene, examining both the environmental benefits in terms of greenhouse gas emission reduction and the economic implications for its adoption. The environmental and economic performance of SAF varies considerably depending on the production pathways and feedstocks employed, with certain combinations demonstrating greater promise in terms of emission mitigation and cost-effectiveness. Therefore, this study concentrates on medium-range routes, for which SAF deployment appears to be particularly promising.

Background [1] [2] [3]

As already broadly demonstrated, climate change is associated to increasingly frequent and intense extreme weather events, with serious consequences for ecosystems, human health, and global economies. The planet is already experiencing a rise in average temperatures and, without immediate and effective action, this trend is expected to accelerate, leading to irreversible damage to biodiversity, water resources, and food security.

The need to limit global warming and mitigate its impacts has never been more urgent. In response to this pressing challenge, the European Union is investing significant resources for research and innovation to address the climate crisis. Specifically, the EU supports collaborative, multidisciplinary initiatives that bring together public and private partners across member states to develop breakthrough solutions that individual countries could not achieve alone through programs such as Horizon Europe.

To achieve the ambitious goal of reducing the environmental impact of aviation in an effective and economically efficient way, innovative approaches are essential and several possible solution are currently being studied. This thesis is partially related to the broader European Project MYTHOS[1], to which Politecnico di Torino gives a substantial contribute, a concrete example of EU efforts targeting medium-range aircrafts to mitigate the environmental footprint of civil aviation through the adoption of Sustainable Aviation Fuels (SAF) and, in the longer term, pure hydrogen. The focus of MYTHOS project is air quality at local level while this thesis will focus on emissions reduction in general, but the two share a common approach and a similar aim: by combining advanced modelling, experimental data, and life cycle assessment, they support the evaluation of emission reductions and cost implications associated with

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[1] This project has received funding from the European Union's Horizon Research and Innovation Programme under grant agreement No 101096286 (https://mythos.ruhr-uni-bochum.de/)

new fuel technologies. The aim is to contribute directly to European decarbonization goals for civil aviation, focusing on short-, medium-, and long-term reductions in CO_2 emissions. The emphasis on the medium-range segment reflects its strategic importance, given its significant share of global air traffic and the balance it offers between operational frequency and payload.

Objectives

This thesis aims to analyse the Life Cycle Assessment (LCA) of Sustainable Aviation Fuels (SAF), with particular emphasis on how production technologies and feedstock types influence overall emissions and associated costs, building upon an holistic and lifecycle-oriented framework.

In this context, this study investigates how different corporate strategies shape the composition of fuel blends used for aircraft refuelling across different geographical regions by analysing five selected international airports taken as reference. The goal is to evaluate both operational and environmental impacts in relation to compliance with current regulations, which foresee a progressive increase in SAF usage within aviation in the coming years.

Eventually, the strategic importance of introducing SAF in a sector characterised by high operational intensity will be highlighted.

The analysis will focus in particular on medium-range routes, which account for a significant portion of global air traffic and offer a meaningful balance between operational frequency and payload. These routes are especially relevant when assessing the impact of SAF, as they provide clearer insights into both the environmental benefits and economic trade-offs associated with integrating sustainable fuels. Moreover, their equal widespread diffusion across different regions makes them ideal for exploring variety in corporate strategies, feedstock availability, production technologies, and regulatory frameworks.

In brief, evaluating the life cycle of SAF within this specific operational segment allows for a more targeted assessment of the environmental effectiveness and economic viability of various solutions. The findings aim is to provide actionable insights for policymakers and industry stakeholders to optimize SAF deployment strategies and support aviation's decarbonization goals.

Contents

In order to improve clarity and accessibility of the present document, a short overview of the contents of each chapter is provided below:

- **Chapter 1** - This chapter points out the environmental impact of commercial aviation, and particularly its contribution to global greenhouse gas emissions. It examines projected air traffic growth until 2050 considering different scenarios and highlights the challenges of reducing emissions while fulfilling a growing travel demand. Eventually this chapter explains the importance of cleaner technologies, sustainable aviation fuels, and targeted mitigation strategies.
- **Chapter 2** - This chapter reviews the critical role of the Intergovernmental Panel on Climate Change (IPCC). It discusses international efforts and frameworks, such as the Science Based Targets initiative and ICAO's long-term aspirational goals, aimed at reducing aviation emissions. The chapter emphasizes the importance of Sustainable Aviation Fuels (SAF) in achieving net-zero emissions, noting their potential to reduce both CO_2 and non-CO_2 climate impacts. It further explores evolving policies and technological advancements like fuel efficiency improvements, electric and hydrogen aircraft.
- **Chapter 3** - This chapter provides an overview of Sustainable Aviation Fuels (SAF) as essential low-carbon alternatives to conventional jet fuels. It covers key feedstocks and production pathways, including biofuels and synthetic fuels, and explains how SAF meet strict sustainability criteria under EU regulations. The certification process ensuring fuel safety and compatibility with existing aircraft is described, alongside the environmental benefits. Then economic consequences and challenges are taken in consideration, tighter with policy

frameworks as critical drivers for SAF adoption. Finally, the importance of diversified feedstocks and targeted investments to support the aviation sector's transition to sustainability is emphasized.

- **Chapter 4** - This chapter examines the environmental benefits and economic implications of Sustainable Aviation Fuel (SAF) adoption for medium-range flight routes across five major international airports, chosen to represent diverse geographic and operational contexts reflecting real-world operations. The study evaluates SAF producers by feedstock and production methods to estimate emissions and costs, to allow for a comparison with conventional Jet A-1 for which data can be obtained through the ICAO Carbon Emissions Calculator.

1. Climate Change and Aviation Emissions [4]

Commercial aviation is a fundamental component of global transportation, enabling rapid movement of people and goods across long distances. Over the past decades, demand for air travel has consistently increased, driven by economic growth, globalization, and advancements in aircraft technology. Today, millions of passengers rely on airlines as a primary mode of transport for both business and leisure purposes.

However, this growth brings significant environmental challenges. Aviation is a major contributor to global greenhouse gas emissions, accounting for a substantial share of transport sector emissions, and its impact on climate change is under increasing examination. The sector's dependence on fossil fuels results in considerable carbon dioxide emissions, which are projected to rise unless effective mitigation strategies are implemented. In addition to CO_2, aviation is responsible for the emission of other pollutants such as nitrogen oxides, particulate matter, sulphur oxides, carbon monoxide, and unburned hydrocarbons, all of which contribute to air quality degradation and pose public health concerns. These non-CO_2 emissions contribute to the formation of contrails and cirrus clouds, which have been shown to exert substantial warming effects, sometimes comparable to or even exceeding those of CO_2 alone.

1.1. Aviation Emissions and Traffic Forecasts [4] [5] [6]

The transport sector, with aviation as a key component, significantly contributes to global greenhouse gas emissions, accounting for approximately 23% of total emissions and 19% of worldwide energy consumption. As can be seen in Figure 1, in 2019 air and maritime transport, both entirely dependent on liquid petroleum fuels, accounted approximately for the 22% of the greenhouse gas emissions released by transports, and to about the 5% of total global emissions. Without the implementation of substantial interventions and the adoption of specific policies, aviation is projected to remain a major contributor to CO_2 emissions in the foreseeable future.

Figure 1 - Global CO2 emissions from transport [7]

In 2023, Air traffic in Europe continued to recover from the impact of the COVID-19 pandemic, reaching 91% of pre-pandemic levels: a total of 8.35 million flights were operated from airports within the EU27+EFTA region, still 9% below 2019 levels. But still, although the recovery seemed to be moderate when looking at the number of flights, passenger numbers increased more rapidly due to a higher average passenger load factor.

Furthermore, the current geopolitical situation is also affecting air traffic: The Russian invasion of Ukraine in February 2022 led to airspace closures and restrictions for operators, significantly impacting traffic flows. Similarly, from October 2023 onward, the conflict in the Middle East also influenced air traffic patterns.

The traffic forecast to 2050 considers three distinct scenarios outlining how European aviation might evolve over the coming decades. These scenarios incorporate a range of factors, including economic growth, travel costs (including both conventional and sustainable aviation fuel prices), sustainability targets and regulations, airport capacity constraints, competition from high-speed rail, and the introduction of new aircraft technologies, fuels, and propulsion systems. Together, they provide a comprehensive framework to understand potential trajectories for air traffic growth and the challenges the sector may face.

Looking ahead, under the "baseline scenario," traffic at EU27+EFTA airports is projected to return to 2019 levels by 2026, followed by a growth to 9.9 million flights in 2030 and 11.8 million flights by 2050. This corresponds to an average annual growth rate of 1.1% between 2025 and 2050. The "high scenario" forecasts a 1.6% annual increase in flights over the same period, whereas the "low scenario" anticipates almost no growth until

2045, expected in case of higher fuel prices. These projections are made of immediate understanding in Figure 2, which clearly illustrates the different growth trajectories for each one of the three scenarios.

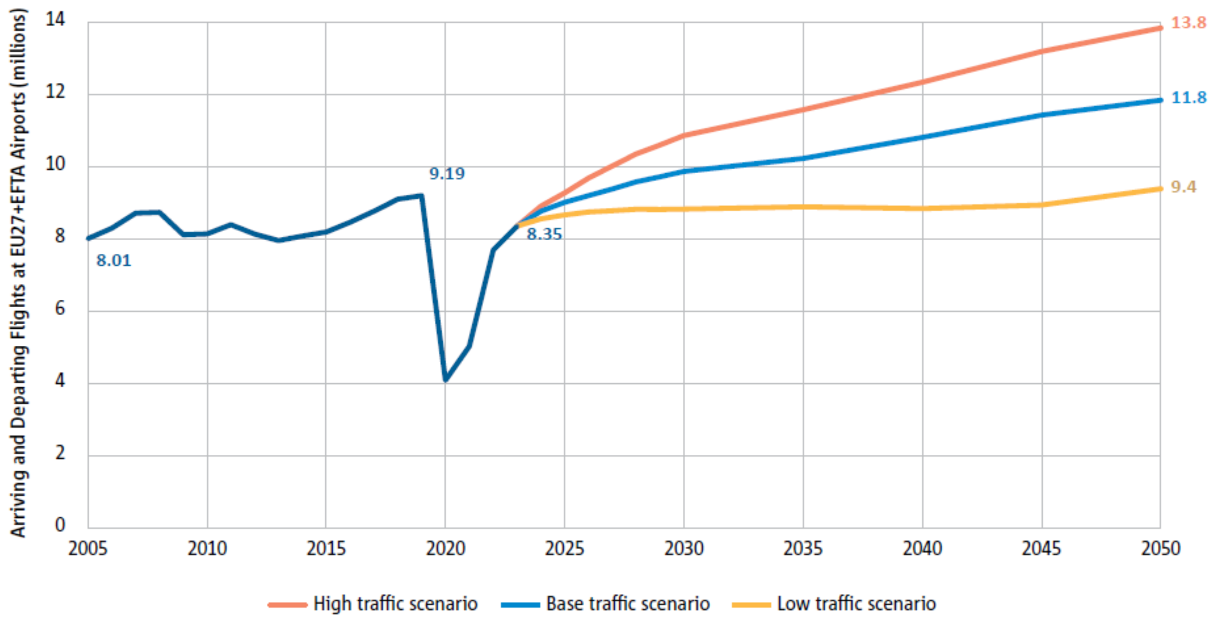


Figure 2 - The numbers of flights are predicted to grow slowly out to 2050 [4]

The year 2019 marked the highest level of CO_2 emissions ascribable to aviation in Europe, with a record of 147 million tonnes produced by flights departing EU27+EFTA airports. The peak was a natural consequence of the overall growth in air traffic in recent years, and was hence related to the sector expansion.

Then, the COVID-19 pandemic in 2020 caused a drastic reduction in emissions, with a notable 57% decrease as air traffic volumes fell to a fraction of pre-pandemic levels. This sudden halt in air travel yielded considerable environmental benefits.

However, as air traffic began to recover since 2021 onwards, emissions started to rise again, reflecting the overall trend of travel demand. It is expected that, with the full post-pandemic recovery of air traffic, emissions will return to pre-2020 levels and, unless effective interventions are taken, even exceed the 2019 record.

To avoid this, several promising measures are being implemented to mitigate aviation's environmental impact, above all the reduction of reliance on fossil fuels, particularly conventional jet fuel.

The European Commission's ReFuelEU initiative, aiming at promoting the use of Sustainable Aviation Fuels (SAF), plays a central role in reducing aviation's carbon footprint. SAFs, derived from renewable sources have the potential to reduce CO2 emissions by up to the 80% in comparison to conventional jet fuel over their entire life cycle. If the EU's SAF targets are met, net CO2 emissions from aviation could be halved by 2050, as projected by the European Commission.

In addition to the deployment of SAFs, the potential of emerging technologies such as electric and hydrogen-powered aircraft further strengthens the prospects for CO2 emission reductions in aviation. Although these technologies are capital-intensive and still in early development stages, they are expected to play a significant role in achieving carbon-neutral aviation by mid-century.

Figures 3 and 4 illustrate the potential impact of the ReFuelEU Aviation mandate on reducing carbon emissions due to air travel across Europe. If the minimum SAF supply targets set by ReFuelEU are met, net CO_2 emissions could be reduced by around 65 million tonnes by 2050. This would represent a 47% drop compared to a scenario without SAF, a significant contribution to the aviation decarbonisation process.

What's shall be pointed out is that, from 2025 onwards, EASA will begin collecting detailed data from both airlines and fuel suppliers on the types of SAF used, their sustainability profiles, and actual CO_2 emissions reductions achieved.

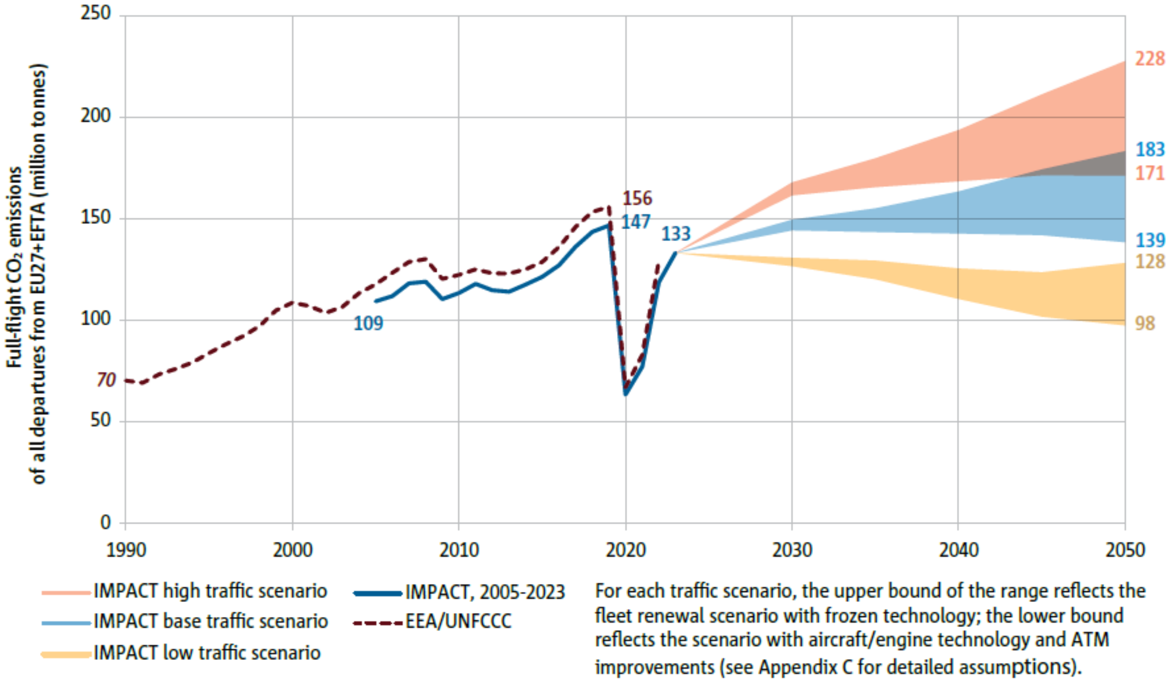


Figure 3 - Full-flight CO2 emissions may grow beyond 2019 levels under the base and high traffic forecast [4]

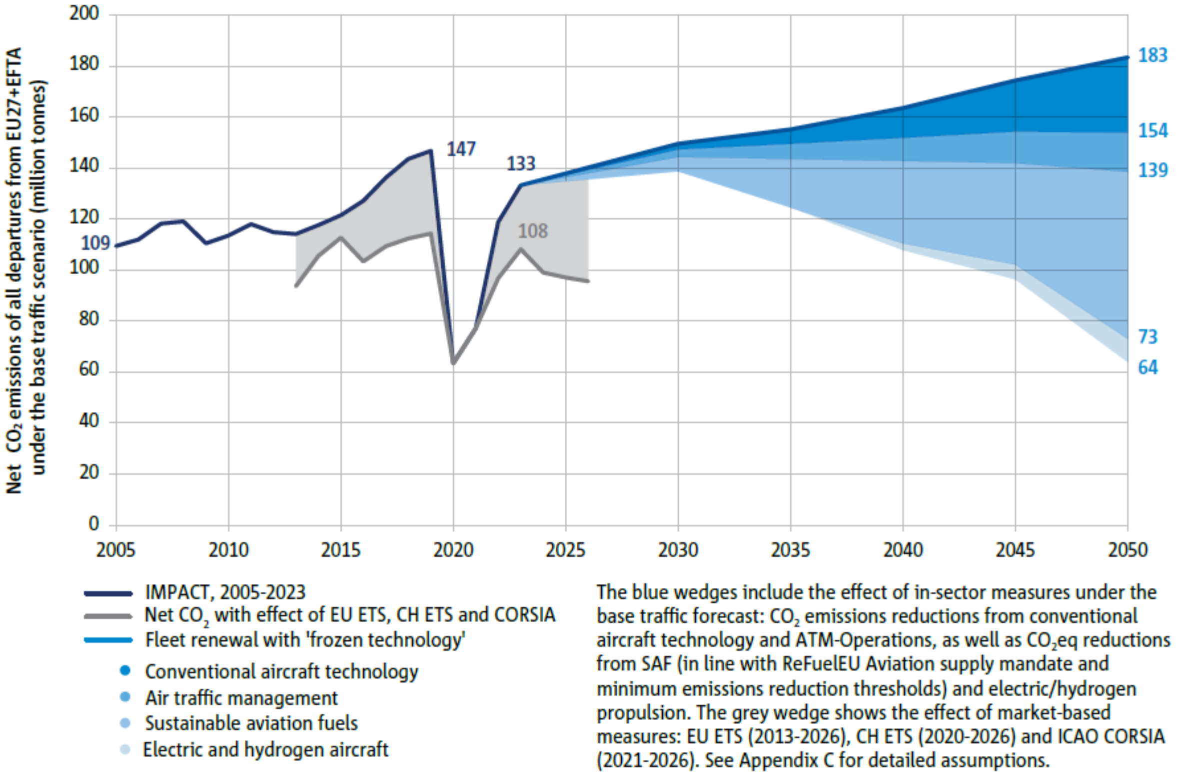


Figure 4 - Net CO2 emissions could be halved by 2050 using sustainable aviation fuels [4]

1.2. Environmental Impact of Flight Categories [4] [5] [6]

Regarding flight categories, long-haul flights (over 4000 km), which accounted for only 6% of departures in 2019, were responsible for nearly 50% of both CO2 and NOx emissions. Conversely, intra-EU+EFTA flights constituted 77% of all flights but accounted for only 39% of CO2 emissions. These data highlight the disproportionate environmental impact of long-distance flights and mark the need for targeted mitigation strategies within different flight segments to effectively reduce aviation's overall emissions footprint. Below, Figure 5 provides an overview of CO_2 emissions share for all flights in-out and within EU27+EFTA grouped according to the region of destination.

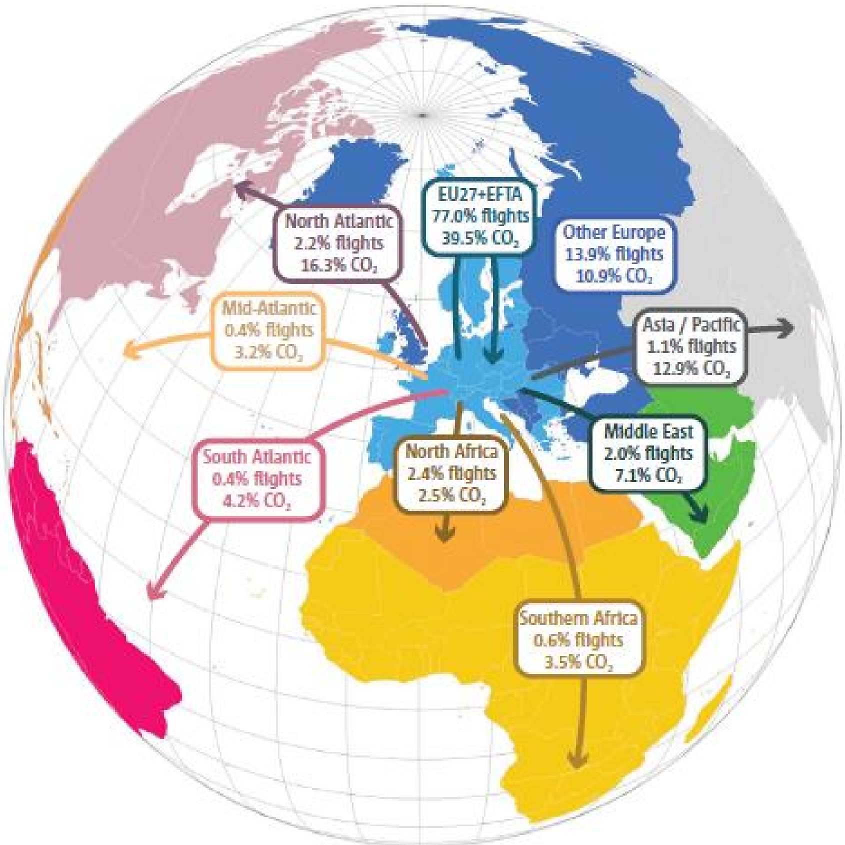


Figure 5 - Share of flights and CO2 emissions by destination region in 2023 [4]

The adoption of cleaner technologies, the use of sustainable aviation fuels (SAF), and more efficient operational practices will be essential to reduce aviation's environmental impact. Advances in the development and implementation of new technologies offer promising prospects for achieving significant reductions in CO2, NOx, PM, CO, and HC emissions over the coming decades. The ongoing progress in clean technologies and supportive policies provides a hopeful outlook for the sector's transition toward sustainability and climate neutrality by 2050.

1.3. Environmental Impact of Aviation [4] [8]

Air pollution has a significant impact on human health, particularly in urban areas. The main atmospheric pollutants include particulate matter (PM), nitrogen oxides (NOx), and ground-level ozone (O3). While overall air pollution has decreased over time, emissions related to aviation have shown an increasing trend. The European Union has established limits for key pollutants such as PM, nitrogen dioxide (NO2), ozone, and sulphur dioxide (SO2) through the Ambient Air Quality Directive. More recently, the World Health Organization (WHO) updated its global air quality guidelines, setting stricter maximum concentration limits for major pollutants to better protect public health.

Specifically, airports are significant sources of localized air pollution, as Aircraft engines release a mix of harmful pollutants, including nitrogen oxides (NOx), particulate matter (PM), volatile organic compounds (VOCs), sulphur dioxide (SO_2), carbon monoxide (CO), and unburned hydrocarbons (HC). Emissions are particularly intense when high thrust levels are required, as for example during take-off manoeuvres, because high temperatures and pressures within engine combustion chambers lead to the release of much greater amounts of nitrogen oxides (NO and NO_2). As confirmed by numerous epidemiological studies, such pollutants have well-documented impacts on human health: exposure can weaken the immune system, impair respiratory function, and increase sensitivity to allergens.

Another concern is ground-level ozone (O_3), a secondary pollutant that forms when nitrogen oxides react with carbon monoxide or VOCs in sunlight. Ozone is a key ingredient in photochemical smog, known for triggering respiratory issues, aggravating asthma, reducing lung function, and even harming crops and natural ecosystems. Elevated ozone levels and other airport-related emissions pose serious challenges not only to public health but also to environmental well-being.

Particulate matter emitted by aircraft consists of small particles, either volatile or non-volatile, varying in size and composition. Aircraft exhaust is a significant source of non-volatile particles, such as soot or black carbon. These fine particles (PM2.5 and smaller) penetrate deep into the respiratory system and have been linked to cardiovascular and respiratory diseases, as well as premature mortality. Although EU regulations set limits for PM10 and PM2.5, ultrafine particles (PM0.1) remain largely unregulated despite emerging evidence of their health risks. Aircraft emissions contribute to elevated particulate matter levels in areas downwind of airports, impacting large populations, especially in cities where airports are close to residential zones. For instance, studies have detected elevated particle concentrations up to 7 kilometres from Amsterdam's Schiphol Airport, highlighting the spatial extent of airport-related pollution. While existing research indicates negative health effects, further studies are required to better understand the relationship between particle size and airport activities.

Sulphur dioxide (SO2) emissions result from the combustion of sulphur-containing fuels. Most sulphur is emitted as gaseous SO2, with a smaller fraction converted into sulphuric acid (H2SO4), which can condense onto other atmospheric particles.

The growing recognition of aviation's contribution to local and regional air pollution highlights the need for integrated mitigation strategies. These include the adoption of cleaner and sustainable aviation fuels with lower sulphur and aromatic content, advancements in engine technology to reduce pollutant formation, and improved operational practices to minimize emissions during ground and flight operations. Additionally, regulatory frameworks and monitoring programs must continue to evolve.

Looking ahead, future scenarios emphasize the importance of balancing CO_2 reductions with the management of non-CO_2 effects. For instance, a study analysing a 2.5% annual reduction in global aviation CO_2 emissions between 2025 and 2050 demonstrated that combining long-term CO_2 reductions with short-term decreases in non-CO_2 emissions can effectively prevent future warming from aviation.

At the same time, it is important to point out the even deeper interconnection between climate and aviation, as the influence is bilateral: aviation has an impact on climate, but at the same time climatic conditions can deeply affect aircrafts operations and their efficiency. Below (see Figure 6) there is an overview of key climate effects on commercial air transport.

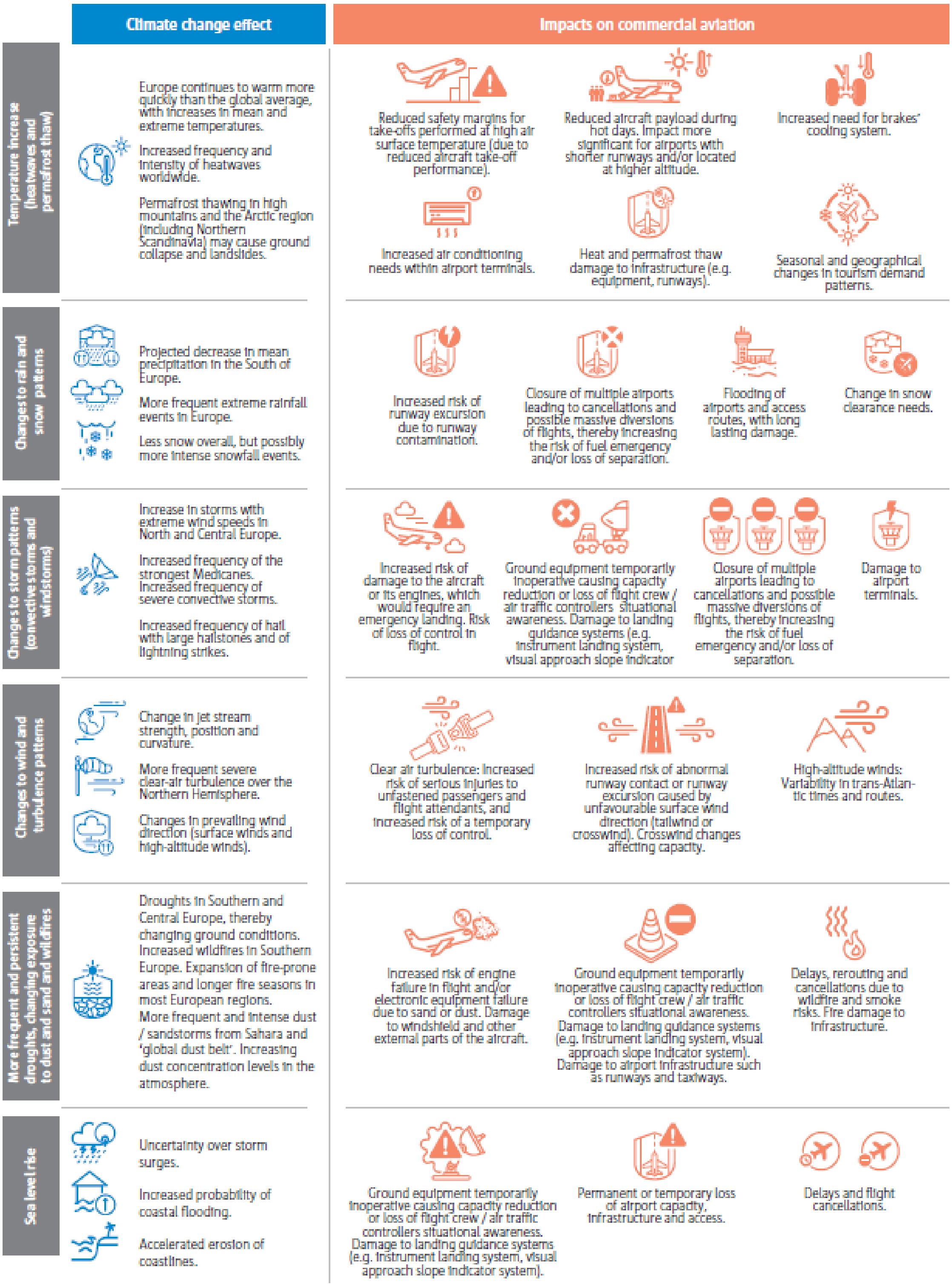


Figure 6 - Climate change risks for commercial air transport [4]

One of the most immediate impacts arises from rising temperatures, especially in Europe where warming is occurring faster than the global average. Higher surface temperatures reduce air density, which diminishes aircraft lift and engine performance during takeoff. This leads to reduced safety margins and forces airlines to limit payloads, particularly at airports situated at higher altitudes or with shorter runways.

Changes in storm patterns further exacerbate risks to aviation. The projected increase in frequency and intensity of convective storms, windstorms, hail, and lightning strikes leads to a greater likelihood of severe turbulence, potential damage to aircraft and engines, and the necessity for emergency landings. Storms can also impair ground operations by damaging critical equipment and landing guidance systems, reducing airport capacity and situational awareness for air traffic controllers. Such disruptions often result in airport closures, flight cancellations and diversions, increasing the risk of fuel emergencies and loss of separation between aircraft.

Rising sea levels and the associated threat of storm surges pose a significant hazard to coastal airports. Flooding and accelerated coastal erosion can cause permanent or temporary loss of airport infrastructure and access routes, severely limiting operational capacity and leading to delays and cancellations.

Furthermore, more frequent and persistent droughts, wildfires, and dust or sandstorms, particularly in Southern Europe, introduce additional challenges. Dust and sand can damage aircraft engines and external surfaces, while smoke from wildfires reduces visibility and air quality, leading to flight disruptions. On the ground, wildfires and dust storms can damage airport infrastructure, impair electronic and navigation systems, and reduce operational capacity.

Together, these climate-driven changes pose significant challenges for commercial aviation, giving further demonstration of the importance of taking rapid and effective action against climate change.

1.4. CO2 Emissions and their role to Climate Change [4] [9]

It is now widely recognized that climate change poses a serious global environmental threat. The climate is strongly influenced by the concentration of greenhouse gases in the atmosphere, such as carbon dioxide (CO_2), which trap infrared radiation emitted from the Earth's surface, creating the natural "greenhouse effect" essential for maintaining life-friendly temperatures. However, human activities over the past century, primarily the burning of fossil fuels, along with agriculture, deforestation, industrial processes, and waste management, have significantly increased the levels of these gases, intensifying the greenhouse effect and causing global warming. This warming leads to widespread consequences, including rising sea levels with the risk of flooding low-lying areas, melting glaciers and sea ice, altered rainfall patterns causing floods and droughts, and more frequent extreme heat events. These changes threaten ecosystems, human health, agriculture, and water resources.

In its 2018 report, the Intergovernmental Panel on Climate Change (IPCC) emphasized the critical importance of achieving net-zero global CO2 emissions to limit global warming to 1.5°C above pre-industrial levels. The subsequent reports have highlighted the urgent need for rapid and large-scale reductions in greenhouse gas emissions across all sectors.

As previously noted, aviation is a significant source of global CO2 emissions, accounting for approximately 2.5% of the total in 2023. The growth in aviation-related emissions has been substantial, with a 47% increase in CO2 emissions since 2000 (as shown in Figure 7). For instance, in 2019, flights departing from EU27+EFTA airports emitted around 156 million tonnes of CO2 equivalent (MtCO2e), representing a 122% increase compared to 1990 levels. By 2022, aviation accounted for roughly 4% of the total greenhouse gas emissions within the EU.

This data underscores the growing environmental footprint of the aviation sector and highlights the challenges faced in aligning its emissions trajectory with global climate objectives.

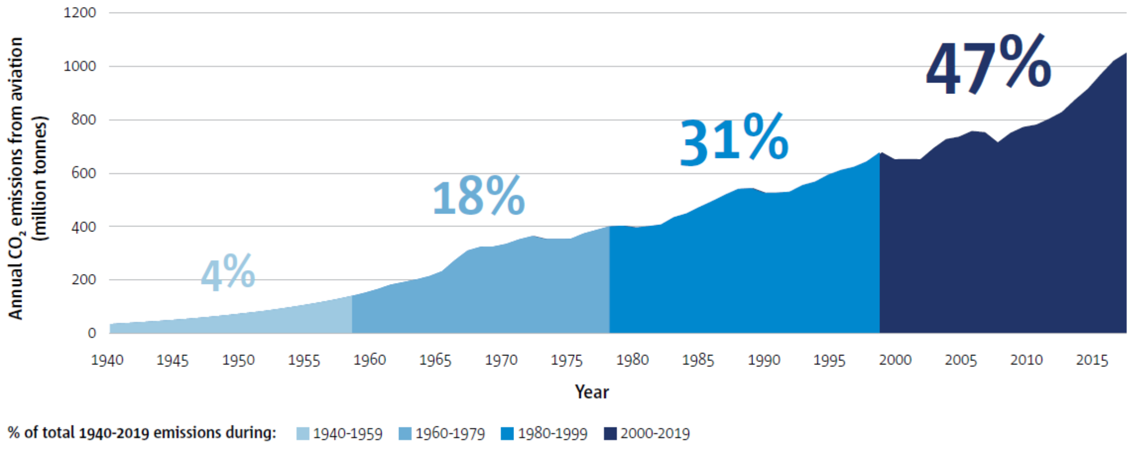


Figure 7 - Annual global CO2 emissions from aviation with % of total cumulative emissions broken down into 20 years periods [4]

1.5. Non-CO2 emissions and their role to Climate Change [1] [10] [11]

As previously discussed, carbon dioxide (CO_2) is the most widely recognised emission from aviation. However, activities within the sector are also responsible for releasing a range of non-CO_2 pollutants, including nitrogen oxides (NOx), particulate matter (soot), sulphur oxides (SOx), and water vapor. These emissions play a crucial role in the formation of condensation trails (contrails), cirrus clouds, and in aerosol-cloud interactions. Scientific research, including IPCC, has demonstrated that non-CO_2 emissions are accountable for a significant portion of aviation's overall climate impact: the Effective Radiative Forcing (ERF) they caused is estimated to account for more than half of the net warming effects attributable to aviation between 1940 and 2018.

Aviation's non-CO_2 emissions are classified as short-lived climate forcers (SLCFs), meaning their climatic effects persist from weeks to decades, in contrast to CO_2, which can remain in the atmosphere for centuries or millennia. Contrails, which form when water vapor condenses at high altitudes, contribute to atmospheric warming by trapping outgoing heat, particularly during nighttime. Persistent contrails can evolve into cirrus clouds, further enhancing this warming effect. At the same time, complex interactions among soot particles, sulphur aerosols, and water vapor result in a mix of warming and cooling effects, depending on atmospheric conditions and particle composition.

Estimating the precise climate impact of these emissions remains challenging due to significant uncertainties, especially regarding aerosol-cloud interactions and the persistence of contrail-induced cirrus clouds. Nevertheless, the combined climate effects of non-CO_2 emissions are considered at least as significant as those of CO_2 alone, underscoring the importance of addressing both with appropriate mitigation strategies.

Fuel composition plays a critical role in non-CO_2 emissions. Fuels with a high aromatic content, particularly naphthalene, a bicyclic aromatic hydrocarbon, tend to produce greater particulate emissions, as aromatics combust more slowly than other hydrocarbons. Consequently, reducing the aromatic content in jet fuel is a promising strategy to mitigate contrail formation and associated non-CO_2 climate impact.

The Sustainable Aviation Fuels are hydrogenated and thus contain no aromatics, this offers a clear advantage in reducing particulate emissions and contrail formation. This underscores the critical role of SAF deployment in effectively lowering both CO_2 and non-CO_2 climate impacts of aviation.

Aviation fuel standards currently set a maximum aromatic content of 25% by volume, with a specific limit of 3% by volume for naphthalene.

The following section (Table 1 and Figure 8) presents a comparative overview of the characteristics of conventional Jet Fuel and SAF.

Composition	*Jet A*	*Jet A-1*
Density at 15°C (kg/m^3)	775-840	775-840
Viscosity (mm^2/s)	8	8
Initial boiling point (°C)	N/A	170
Final boiling point (°C)	300	300
Minimum Flashpoint (°C)	38	38
Total acidity (mg KOH/g)	0.1	0.1

Freezing point (°C)	-40	-47
Aromatics (wt %)	18.53	18.0
Cycloparaffins (wt %)	31.80	N/A
n-paraffins (wt %)	19.98	N/A
Iso-paraffins (wt %)	29.69	N/A
Net heat of combustion (MJ/kg)	43.28	42.8

Table 1 - Properties of standard specification fuels (Jet A and Jet A-1) [12]

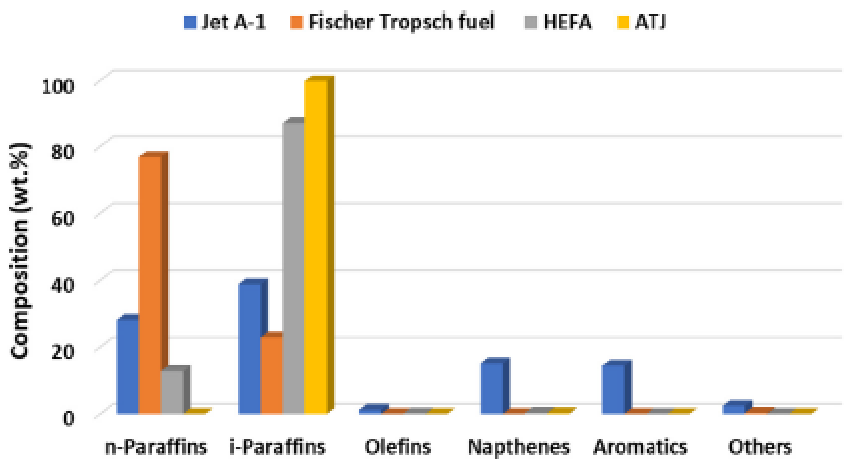


Figure 8 - Compositional analysis of different SAF [12]

1.5.1. Non-CO_2 Emissions from Aviation: Environmental Impacts [4] [5] [6]

In 2022, flights departing from EU27+EFTA airports accounted for 12% of total greenhouse gas (GHG) emissions within the transport sector and 4% of the region's overall GHG emissions. Aviation emissions in 2022 nearly returned to pre-COVID levels, marking a significant increase of 84% compared to 1990. This growth positioned aviation as the third-largest source of GHG emissions in the transport sector, following road and maritime transport. The expansion of air traffic has been the primary driver of these increases, which have not been sufficiently mitigated by advances in engine technology and operational improvements.

Beyond CO_2, aviation also contributes significantly to other environmental pollutants, notably nitrogen oxides (NOx) and particulate matter (PM). In 2022, aviation-related NOx emissions represented 14% of total NOx emissions in the transport sector across the EU27+EFTA. Additionally, aviation was responsible for 4% of total PM2.5 emissions in the same region. NOx emissions, which include nitrogen monoxide (NO) and nitrogen dioxide (NO_2), are generated by fuel combustion in aircraft engines. These emissions play a critical role in the formation of ground-level ozone and smog, both of which have detrimental effects on human health and the environment. Furthermore, NOx contributes to the formation of fine particulate matter (PM), exacerbating atmospheric pollution.

Since 2005, NOx emissions from flights departing EU27+EFTA airports have increased by 46%, largely due to the growth in flight numbers and the distances flown. Although technological advancements, such as more fuel-efficient engines and improvements in air traffic management, have helped to slow the growth rate of NOx emissions, they have not been sufficient to reverse the overall upward trend. Emerging engine designs, including those incorporating hybrid-electric systems, along with enhancements in air traffic management, such as optimized flight planning and landing procedures, are expected to stabilize NOx emissions at 2019 levels by 2050, with particulate matter emissions also projected to decline.

Another key pollutant that causes great concern is carbon monoxide (CO), which is produced during incomplete combustion reactions. Although CO emissions have increased at a slower rate compared to NOx or PM, they still represent a significant environmental challenge. In recent years, CO emissions have risen by a factor between 4% and 13%, depending on the specific aircraft and operating conditions. While CO emissions have a lesser impact on global climate than CO_2, they contribute to poor air quality problems.

Additionally, aviation is responsible for emissions of unburned hydrocarbons (HC), which contribute to the formation of ozone and smog. HC emissions have increased, albeit at a slower pace compared to other pollutants, and are expected to decline with future advancements in engine and combustion technology. The chart shown in Figure 9 provides relevant statistics about the various pollutants so far considered. On one hand, emissions of nitrogen oxides (NOX) and, to a lesser extent, volatile particulate matter (PM) are expected to increase over the coming decades. Reducing these pollutants remains a significant challenge and will require sustained and targeted efforts. On the other hand, emissions of carbon monoxide (CO), unburnt hydrocarbons (HC), and non-volatile PM are projected to stabilize or even decline by 2050. This positive trend is largely due to fleet renewal and improvements in air traffic management (ATM) systems.

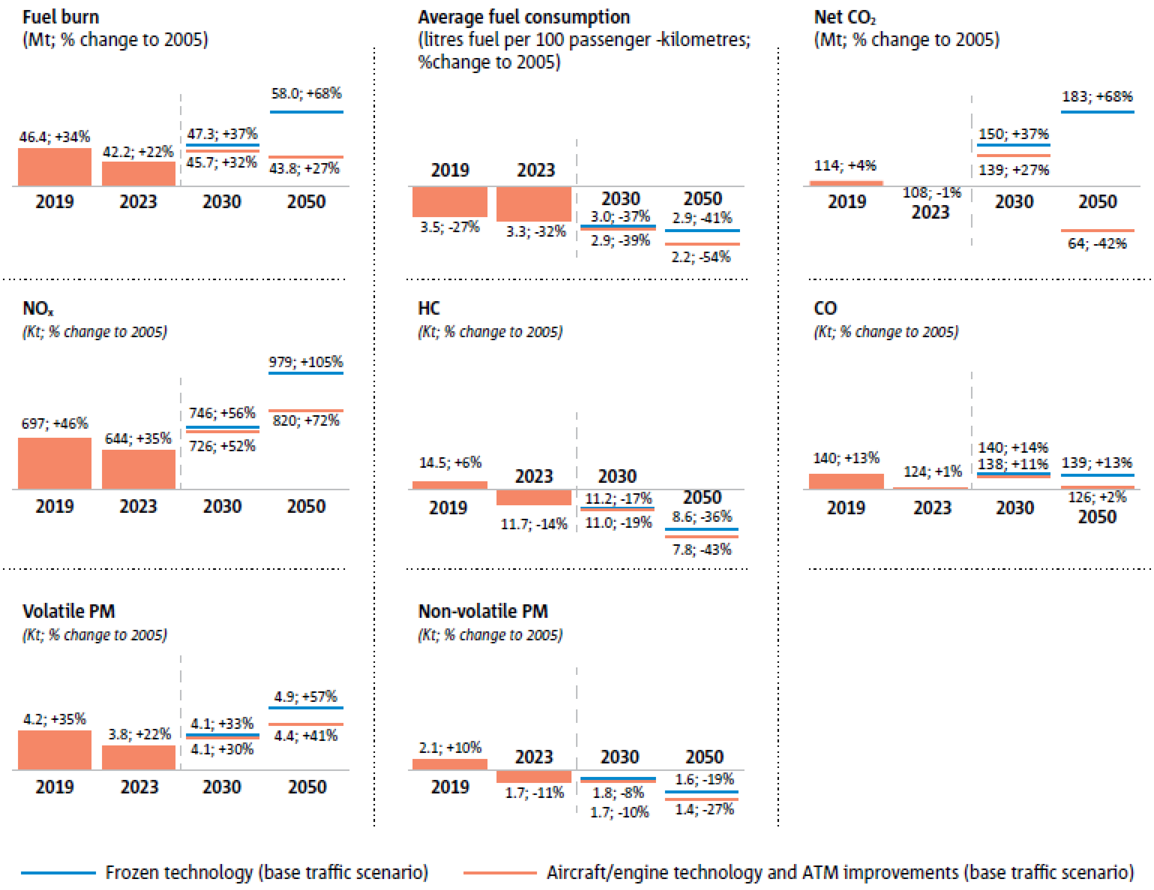


Figure 9 - Summary of full-flight emission indicators (% change to 2005) [4]

1.5.2. Non-CO_2 Emissions from Aviation: Health Impacts [4] [5] [6]

The increase in particulate matter (PM) emissions from aviation is particularly concerning due to the adverse health effects these pollutants have, which are linked to respiratory and cardiovascular diseases. Nitrogen oxides (NOx), through their role in forming ground-level ozone and smog, also pose significant risks to human health and the environment.

Carbon monoxide (CO) emissions, although less impactful on global climate, contribute to poor air quality and can adversely affect the health of populations living in close proximity to airports. Exposure to elevated CO levels can impair cardiovascular and respiratory function, especially in vulnerable groups such as children, the elderly, and individuals with pre-existing health conditions.

Unburned hydrocarbons (HC) emitted by aircraft engines further exacerbate air pollution by contributing to ozone and smog formation, which are associated with a range of health problems including asthma, lung inflammation, and other respiratory illnesses.

Overall, the growth in aviation-related emissions of NOx, PM, CO, and HC represents a significant public health challenge, particularly for communities near major airports. While technological and operational improvements are expected to mitigate some of these impacts in the future, ongoing monitoring and targeted policies remain essential to protect human health.

1.6. Contrail formation and their climate impact [4] [13]

As previously explained, contrail formation and their evolution into cirrus clouds represent a critical area of study to understand aviation's climate effects. Contrails- short for condensation trails-initially appear as thin, linear clouds behind aircraft flying at high altitudes. Under suitable atmospheric conditions, these contrails can persist for hours and eventually merge with natural cirrus clouds. The climatic properties and impact of these contrail-induced cirrus clouds vary depending on factors such as time of day, altitude, and prevailing meteorological conditions.

Research has highlighted the essential role of soot particles and other aerosols emitted by aircraft engines in contrail formation. These particles serve as ice nuclei around which ice crystals form, significantly influencing the microphysical characteristics and persistence of contrails. Moreover, aircraft emissions also affect the formation of natural clouds and can alter natural cloud formation processes, particularly affecting cloud properties in the mid-troposphere. This effect has not yet been included in many models of the climate impact of contrails, indicating a gap in current understanding.

Figure 10 shows the different stages of contrail formation and their impact on the climate.

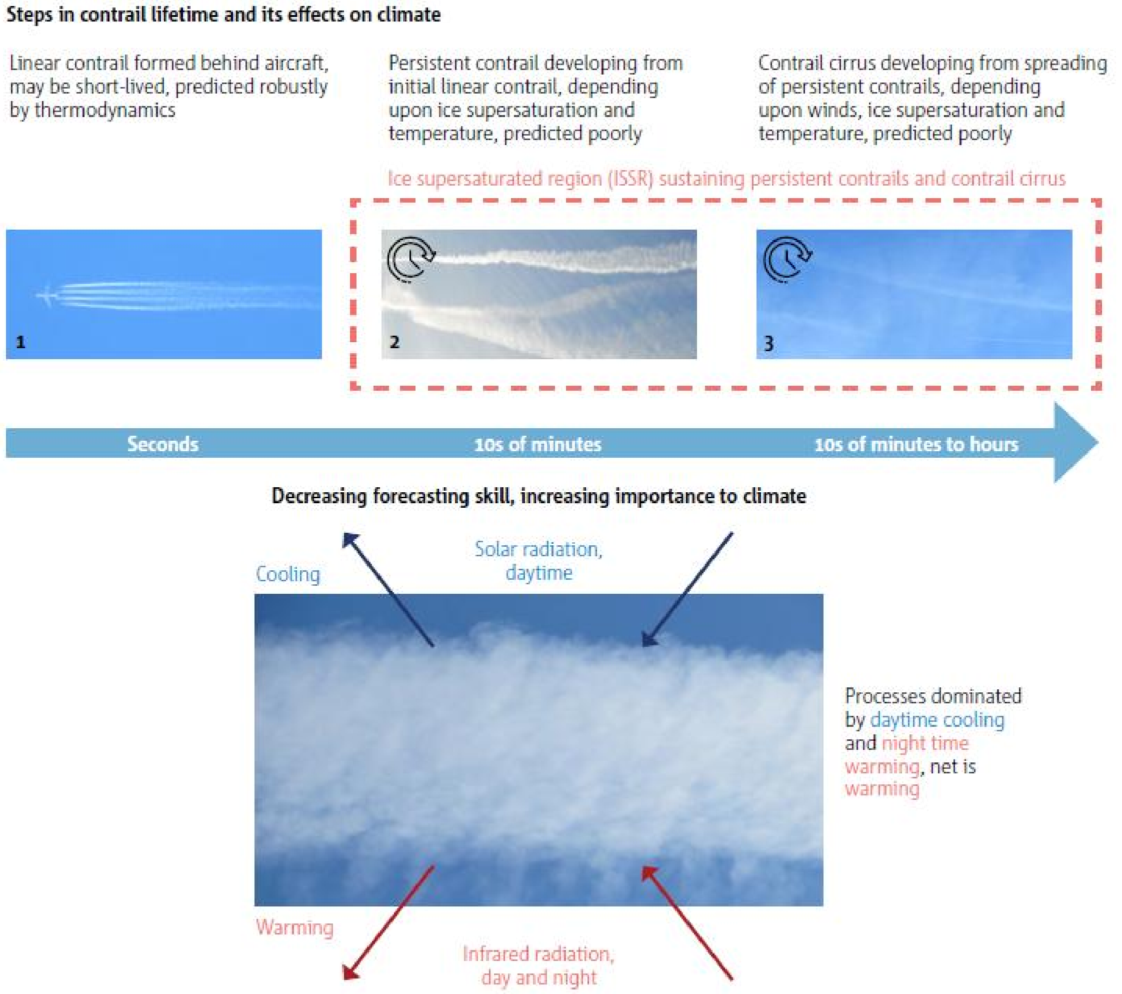


Figure 10 - The formation of contrails and timescales [4]

Persistent contrails form when hot, humid exhaust gases from aircraft engines mix with cold, moisture-saturated air at high altitudes, particularly within ice-supersaturated regions (ISSRs). In these conditions, contrails can persist and spread, transforming into cirrus clouds that trap outgoing longwave radiation and contribute to a net warming effect on the climate.

The effect of contrails is that of reflecting longwave heat radiation. During the day longwave radiation emitted by the Earth's surface is bounced back, preventing it from escaping into space, but simultaneously the same happens with the sun radiation, preventing it from reaching the planet's surface and therefore partially compensating the warming "greenhouse" effect. During nighttime though, contrails warming effect is significantly stronger, as they still trap outgoing longwave radiation, but without the beneficial reflection of sun heat as a counterbalance. As a consequence, the climatic impact of contrails is particularly significant during evening and nighttime hours (refer to Figure 11 for a schematic illustration of the phenomenon).

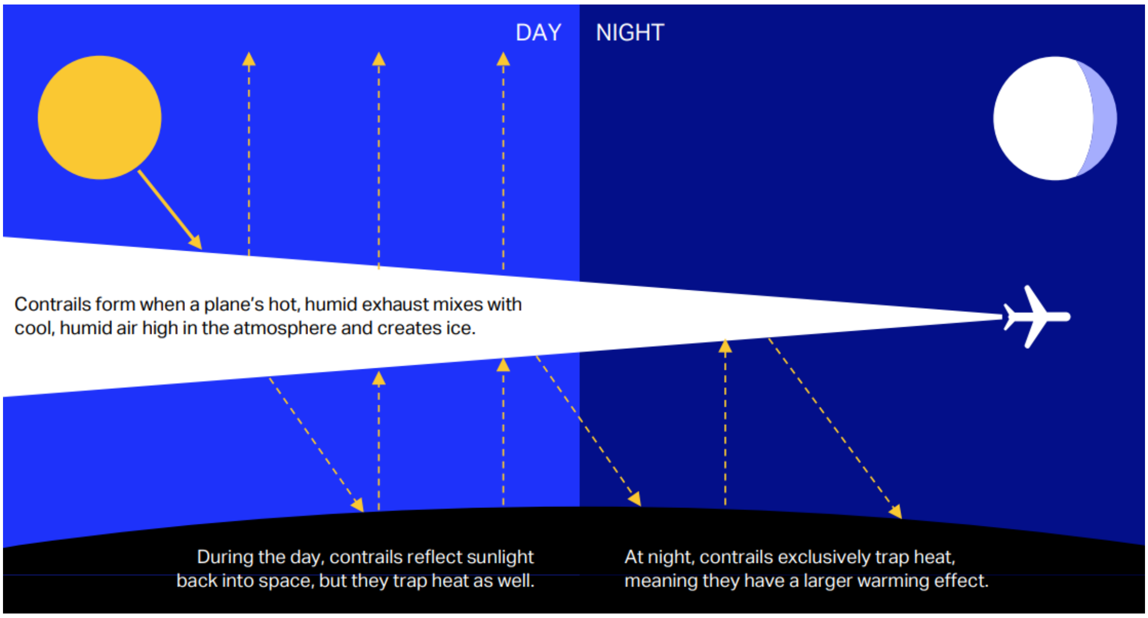


Figure 11 - Illustration between day and night contrails [13]

As a consequence, a small subset of flights (less than 3% globally) accounts for around 80% of contrail-induced warming. This concentration suggests that targeted operational measures could yield disproportionate climate benefits.

Several mitigation strategies are currently under investigation. These include:

- Optimizing flight routes to avoid ISSRs, thereby reducing contrail formation. Dynamic air traffic management and real-time atmospheric data integration can enable such route adjustments without compromising safety or efficiency.

- Advancing engine technologies to lower soot particle emissions, which serve as nuclei for ice crystal formation.
- Deploying sustainable aviation fuels (SAF) with reduced aromatic content, which can decrease particulate emissions and thus the contrail development.

Operational studies have demonstrated that relatively minor adjustments in flight altitude or routing can significantly reduce contrail formation and their climate impacts.

2. The challenge of Decarbonizing Aviation in the context of Global Climate Change [4] [9] [14]

Efforts to mitigate aviation's climate impact are increasingly urgent as global temperatures rise and emission reduction targets become more ambitious. The Intergovernmental Panel on Climate Change (IPCC) has highlighted the critical role of reducing greenhouse gas emissions globally. Despite efforts to improve fuel efficiency, the rapid growth in air traffic challenges the sector's ability to meet ambitious climate targets. Sustainable Aviation Fuels have emerged as a key solution, offering substantial reductions in lifecycle CO_2 and non-CO_2 emissions. Complementary technological innovations, such as electric and hydrogen propulsion, alongside operational improvements and robust policy frameworks are essential to drive the sector's transition towards sustainability. Coordinated global action and continued research will be vital to overcoming economic and technical barriers and achieving meaningful emission reductions in aviation.

2.1. The Role of the IPCC and the Challenge of Decarbonizing Aviation [4] [9] [14]

The Intergovernmental Panel on Climate Change (IPCC) plays a pivotal role in providing scientific assessments to inform and guide policymaking. In 2023, the IPCC released its Synthesis Report, which unequivocally established the link between human activities, primarily greenhouse gas (GHG) emissions, and global warming. By 2023, global surface temperatures had already risen by 1.1°C above pre-industrial levels, with future projections indicating further warming scenarios depending on emission levels. The consequences of this warming are evident in the increasing frequency and severity of extreme weather events, sea level rise, and accelerated ice melt.

Within this context, as previously explained, aviation remains a significant contributor to global climate change. In 2023, aviation, together with maritime shipping, accounted for approximately 5% of global CO2 emissions. Projections suggest that, without substantial mitigation, emissions from aviation and shipping could consume between

60% and 220% of the allowable CO2 emissions by 2050, underscoring the urgent need for decarbonization in these sectors to achieve global climate targets.

In response to these challenges, various international organizations are developing frameworks to support the aviation sector in meeting emission reduction goals. In 2021, the Science Based Targets initiative (SBTi) issued guidelines to help airlines set CO2 reduction targets aligned with the Paris Agreement, which calls for substantial emission cuts by 2050. In 2022, the International Civil Aviation Organization (ICAO) advanced this agenda by publishing a report assessing the feasibility of long-term aspirational goals (LTAG) for CO2 reductions in international aviation.

Despite these efforts, the decarbonization of aviation faces significant obstacles, primarily due to the rapid growth in air traffic, which has outpaced improvements in fuel efficiency. Addressing aviation emissions will require not only technological and operational advancements but also a comprehensive global approach that includes the development and deployment of sustainable fuels, such as biofuels and hydrogen.

SAF is essential to achieving net-zero emissions in the aviation sector; if produced from feedstocks like waste oils, agricultural residues, and purpose-grown energy crops have the potential to reduce lifecycle CO_2 emissions by up to 80% compared to conventional jet fuel. Moreover, SAF not only reduce CO_2 emissions but also contribute to lowering non-CO_2 climate impacts, such as contrail formation, due to their lower aromatic content.

Tackling aviation’s emissions is essential not only for meeting the global climate objectives set out in the Paris Agreement but also for mitigating the impacts of extreme weather events and other climate-related risks that are already affecting millions of people worldwide. The integration of SAF and emerging technologies, combined with supportive policies and international collaboration, will be critical to steering the aviation industry toward a sustainable and climate-neutral future.

2.2. Policies for emission reduction in aviation sector [4] [5] [9] [15]

Since the 1999 IPCC Special Report, scientific understanding of aviation's climate impact has become increasingly detailed. Initially, the primary focus was on CO_2 emissions, recognised as a major driver of global warming.

Hence, by 2020, aviation's effects were reassessed using Effective Radiative Forcing (ERF), a more comprehensive metric that accounts not only for direct CO_2 emissions but also for non-CO_2 contributions, including aerosol-cloud interactions, sulphur compounds, and soot particles. As discussed previously, non-CO_2 emissions are more challenging to quantify and involve greater uncertainty, but they have been found to contribute substantially to aviation's overall climate impact. Recent studies suggest that non-CO_2 effects-such as contrail formation and contrail-induced cirrus clouds-may have a warming effect equal to or even exceeding that of CO_2 emissions.

Given these findings, the European Union and international organizations have shifted toward more holistic mitigation strategies. Notably, in 2025, the EU Emissions Trading System (ETS) was updated to incorporate not only CO_2 emissions from aviation but also non-CO_2 effects, integrating measures related to contrail formation and aerosol-cloud interactions into its monitoring, reporting, and verification (MRV) framework.

This represents a significant advancement in regulatory approaches, acknowledging that addressing aviation's climate impact requires tackling both CO_2 and non-CO_2 emissions to achieve long-term climate goals.

As previously mentioned, one of the primary mitigation strategies to reduce both CO_2 and non-CO_2 emissions is the development and adoption of Sustainable Aviation Fuels. SAF contain significantly lower concentrations of aromatic compounds and sulphur, which leads to reduced particulate emissions, thereby helping to limit contrail formation and the persistence of contrail-induced cirrus clouds. However, despite the significant potential of SAF to reduce emissions, they alone may not be sufficient to offset the rapid growth in aviation emissions, which are expected to continue rising in the coming decades due to expanding air traffic. Therefore, further research is essential to optimize SAF formulations to further minimize their climate impact.

In parallel with the deployment of Sustainable Aviation Fuels (SAF), continuous improvements in fuel efficiency are being pursued through the introduction of new technologies aimed at reducing aircraft weight and aerodynamic drag. Modifications such as advanced wingtip devices are an example of these incremental advancements, which collectively contribute to lowering fuel consumption and emissions per flight.

In addition, electric aircraft are anticipated to be deployed commercially for short-haul flights with limited passenger capacity. Since approximately 80% of aviation emissions originate from flights exceeding 1500 km, the overall impact of electric aircraft on emission reductions will be limited. Hydrogen-powered aircraft may be suitable for long-haul and larger aircraft; however, their potential is still under evaluation. Although hydrogen propulsion eliminates CO_2 emissions, it may still contribute to NO_x and water vapor emissions, which, if not properly managed, could contribute to warming effects.

To overcome these difficulties, the European Union established the Aviation Non-CO_2 Experts Network (ANCEN), aiming to bring together stakeholders from across the aviation sector to coordinate efforts focused on non-CO_2 emissions. ANCEN also seeks to improve data collection and climate modelling capabilities, providing more accurate tools to design effective emission reduction strategies and support future regulatory decisions.

While regulatory measures addressing aviation CO_2 emissions have long been implemented, the recent inclusion of non-CO_2 emissions within the EU Emissions Trading System (ETS) marks a significant step in addressing the aviation's full climate impact. This evolving approach is also reflected in global strategies, with the International Civil Aviation Organization (ICAO) actively working to integrate climate change considerations into aviation policies and strategies.

3. Sustainable Aviation Fuels (SAF) [4] [5] [6] [16] [17]

As discussed in the previous chapters, the aviation sector is a significant contributor to global greenhouse gas emissions, with both CO_2 and non-CO_2 pollutants playing critical roles in climate change. Despite technological improvements and operational measures, the rapid growth of air traffic continues to challenge efforts to reduce the sector's environmental footprint. In this context, ReFuelEU is a crucial attempt to make air travel more sustainable by promoting a wider use of Sustainable Aviation Fuels (SAFs in brief) in Europe thanks to specific legislation.

SAFs have emerged as one of the most promising solutions to achieve substantial emission reductions, thanks to their potential to lower lifecycle CO_2 emissions and mitigate non-CO_2 climate impacts such as contrail formation. For these reasons, ReFuelEU will make SAF use mandatory from 2025 onward, including specific sub-targets for synthetic aviation fuels. This regulatory framework shift doesn't just account for the rising attention towards SAF on the international scenario, but also for the urgent need to scale up fuel production and infrastructure to keep pace with the sector's evolving climate goals.

3.1. Production pathways and sustainability criteria [4] [5] [17] [18] [19]

Sustainable Aviation Fuels are alternative fuels developed to replace conventional fossil-based jet fuels. They are produced through different innovative processes, all aimed to reduce greenhouse gas emissions in comparison to traditional aviation fuels. SAF can divided into biofuels, derived from organic feedstocks, and synthetic fuels, produced using renewable energy sources and carbon capture technologies. Each follows its own production process and is defined by specific regulations.

According to the European Union's ReFuelEU Aviation regulation, SAF are classified as "drop-in" fuels. This means they are totally compatible with existing technologies, aircraft engines, and fuelling systems and therefore their use does not require any technical changes to aircrafts or fuel supply systems. This compatibility feature is particularly significant, as it facilitates the integration on SAFs into the current aviation fuel supply chain, potentially accelerating their adoption.

SAF can be produced from many feedstocks, including waste oils and animal fats, lignocellulosic biomass, agricultural and forestry residues, municipal solid waste, and even synthetic processes powered by renewable electricity. As better explained in the next sections, it is important to point out that these feedstocks do not compete with food crops or require additional land use. This helps avoid problems like deforestation, damage to ecosystems, and biodiversity loss.

To be considered truly sustainable, SAF must meet the criteria set by the Renewable Energy Directive II (RED II). The aim is that of assure that these fuels offer a real reduction in greenhouse gas emissions compared to traditional aviation fuels. For example, biofuels produced from plants and commissioned before October 2015 must achieve a minimum emission reduction of at least the 50%, while those commissioned after January 2021 face a stricter requirement: a reduction of at least the 65%. Meeting these targets is essential not only to support climate goals but also to make SAF eligible for public funding.

On the other hand, synthetic fuels, often referred to as e-fuels, can aim at even more ambitious achievements: if these are produced using renewable electricity and with CO_2 captured directly from the air, the potential to reduce direct emissions can nearly reach the 100%, opening the potential for carbon neutrality. However, when considering the full lifecycle (including emissions from transportation and supply chains) complete carbon neutrality cannot be achieved.

Sustainable Aviation Fuel can be produced through a range of different processes, each varying in technological maturity, scalability, and sustainability credentials. Some of the most promising and commercially relevant pathways are hence described hereafter.

3.1.1. Hydroprocessed Esters and Fatty Acids (HEFA)

HEFA is currently the most commercially mature and viable SAF production pathway, with a high Technology Readiness Level (TRL of 8-9). This process converts waste fats (such as used cooking oil and animal fats, collectively known as FOGs) as well as vegetable oils (like jatropha and camelina, known as Hydrotreated Vegetable Oil, HVO) into jet fuel. HEFA technology has already proven itself to be fully scalable and commercially viable, with large production plants capable of producing one billion litres per year already active. However, only about 15–20% of the output these plants produce is biojet fuel; the remaining 80% is mostly renewable diesel. Companies such as Neste are leading the expansion of biojet production, heavily investing in new facilities. That said, the expansion of HEFA-based SAF is limited by the high cost and availability of oleochemical feedstocks, alongside sustainability concerns related to crop-based oils. This has led to increased use of waste lipids, which price has risen due to growing demand. In short, the future of HEFA will depend heavily on feedstock availability, affordability, and environmental impact.

3.1.2. Alcohol-to-Jet (AtJ)

AtJ fuels are produced by fermenting biomass, such as agricultural residues or crops like corn, sugarcane, and wheat into alcohols which are then converted into jet fuel. AtJ technology is still emerging, with a Technology Readiness Level (TRL) of 7 to 8. One advantage is that the fuel produced through this process has a low aromatic content, therefore helping reduce non CO2 emissions. The process has been so far tested using two main alcohols: isobutanol and ethanol. Both were approved by ASTM for blending with conventional jet fuel, in a percentage up to 50%. This method, as HEFA or other thermochemical processes, also produces biodiesel as a co-product but, unlike what other methods typically offer, AtJ can theoretically produce jet fuel at yields of up to 70%: a significantly higher percentage. However, the market value of the alcohol intermediates remains a key challenge: Isobutanol, for example, is often more valuable as a chemical feedstock than as an input for SAF production; ethanol, on the other hand, is already widely used in road transport, and this causes competition. Sustainability of the feedstock is also critical, as it directly affects the carbon footprint of the final biojet fuel. While corn-based sources can lead to relatively low emissions, lignocellulosic biomass, which doesn't compete with food production, is expected to have much better climate performance, mainly due to its lower impact on land use and ecosystems.

3.1.3. Biomass Gasification + Fischer-Tropsch (Gas+FT)

GAS+FT pathway works by turning biomass or municipal solid waste (MSW) into a gas mixture called syngas, which is then converted into jet fuel through the Fischer-Tropsch process. Although the method shows strong potential, it hasn't yet been rolled out on a commercial scale in the EU. The process begins with gasification, where organic materials are exposed to high temperatures. This breaks them down into syngas, a mix mainly made of hydrogen (H_2) and carbon monoxide (CO). After that, the syngas goes through the FT process, which uses catalysts to synthesize liquid hydrocarbons like diesel, jet fuel, gasoline, and other useful products. However, commercializing biojet fuel from biomass via gasification faces several technical and economic challenges. Biomass gasification can produce a lot of tar, which requires intensive cleaning. The high oxygen content in biomass also lowers the energy value of the syngas compared to natural gas. And there are other complications too, syngas from biomass often contains nitrogen, sulfur compounds, and other impurities that can damage the FT catalysts unless removed thoroughly. To overcome these challenges, biomass, and MSW, derived syngas must be cleaned and enriched with extra hydrogen before FT conversion. From an economic perspective, gasification and FT synthesis technologies involve high capital investment and operational costs. On top of that, biomass has a relatively low energy density, which makes it harder and more costly to collect and transport. Even so, FT-based processes can convert about 40% of the output into jet fuel and middle distillates. The rest is made up of other hydrocarbons, which can still be refined or used for other industrial applications.

3.1.4. Power-to-Liquid (PtL)

PtL fuels are seen as one of the most promising options for scaling up SAF production. They offer a path toward truly carbon-neutral, or even carbon-negative, fuels. The key step in PtL process is the use of renewable electricity sources (such as wind, solar, or hydropower) to split water and produce hydrogen through electrolysis. This hydrogen is then combined with carbon monoxide (CO) or carbon dioxide (CO_2) captured from industrial waste gases, biomass processing, or direct air capture (DAC) technologies. The result is a synthetic liquid fuel, created through processes like Fischer-Tropsch synthesis, that can be used just like conventional jet fuel.

Despite their potential, PtL fuels currently face significant cost challenges. Production requires massive investments in renewable energy capacity and advanced electrolysis and synthesis infrastructure. Right now, it's economic feasibility depends strongly on supporting policies, such as carbon pricing and public funding. At the same time, clear sustainability standards are essential to ensure these fuels really deliver climate benefits. Although production costs are expected to fall as the technology improves, PtL fuels will likely face tough competition from other SAF options in the near future. However, PtL fuels stand out for their potential to achieve very significant emission reductions, including the possibility of negative emissions when produced using CO_2 from direct air capture combined with bioenergy and carbon capture and storage (BECCS).

The diagram displayed in Figure 12 summarises the various feedstocks, processes, and technologies involved in SAF production, illustrating the diversity of pathways available to meet future aviation fuel demands sustainably.

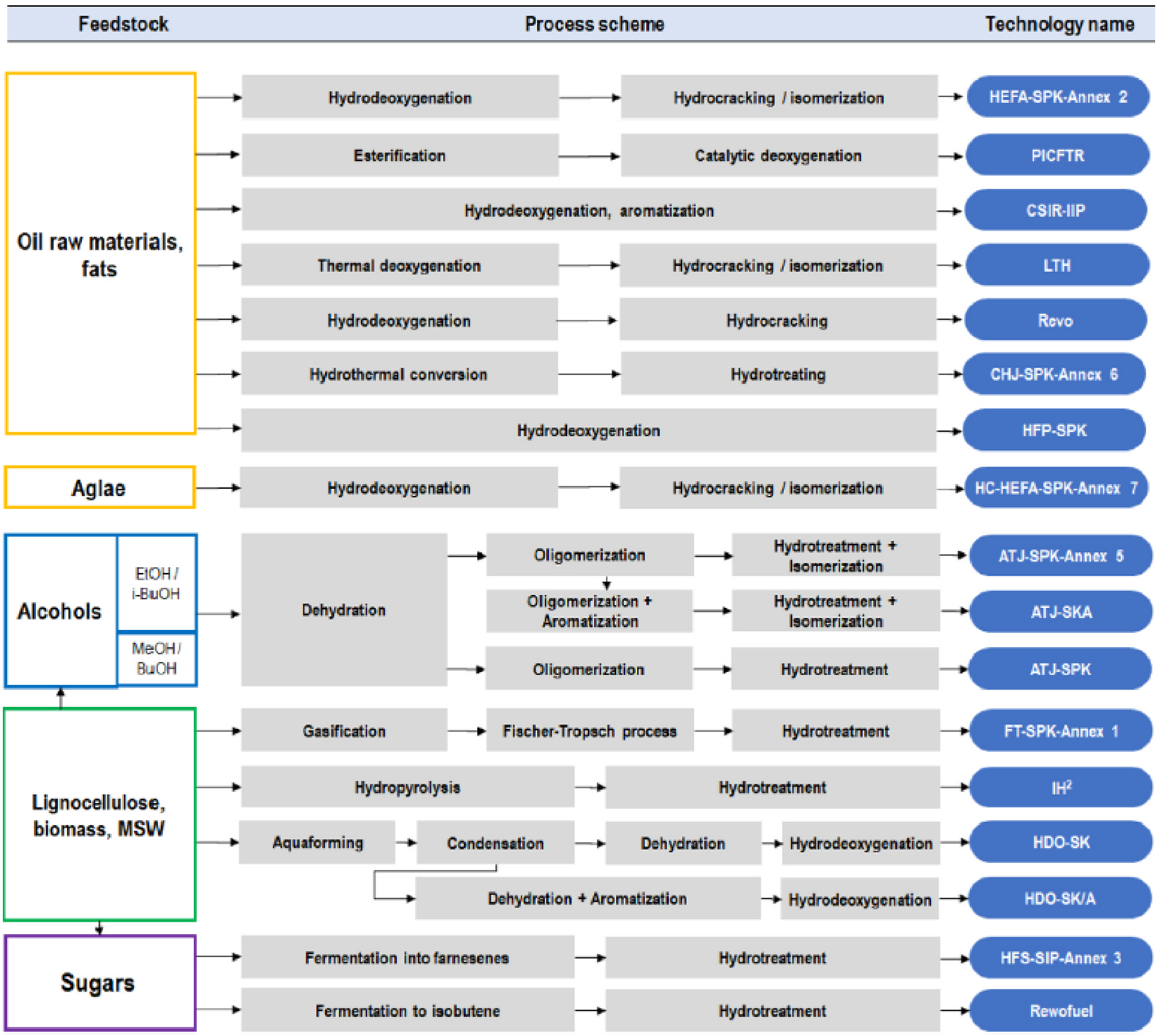


Figure 12 - Technologies for the SAF production from different groups of raw materials [6]

3.2. Certification and Standardization of Sustainable Aviation Fuels [4] [5] [17] [18] [19]

Aviation fuel is subject to strict safety and performance standards, which are crucial to guarantee aircraft's safe operations. These standards are regulated by organizations such as ASTM International, through the ASTM D1655 specification, and the United Kingdom's Ministry of Defence via DEF STAN 91-091, among others. As of October 2024, eight Sustainable Aviation Fuel production pathways had been standardized by ASTM and integrated into other fuel standards.

Scaling up SAF production requires a rigorous qualification process involving extensive testing and validation of fuel samples. Every new fuel type must undergo extensive testing to confirm it performs safely and reliably in real flight conditions. This process is outlined in the ASTM D4054 protocol, and while it's time-consuming and expensive, it's essential for certification and commercial use. D4054 offers two certification tracks: a standard and an accelerated process. Both involve multiple testing phases:

- Initial screening (Levels 1 and 2): evaluates the fuel's technical properties and suitability for aviation.
- Component and engine testing (Levels 3 and 4): tests are carried out on fuel system components and actual engines.
- Approval of specification changes: confirms the new fuel can meet all ASTM standards and be blended safely with conventional jet fuel

The accelerated certification pathway helps reduce both time and cost, but limits the allowable SAF blend ratio to 10% with conventional jet fuel.

The expansion of SAF production faces challenges: progress is still slowed by technological limitations, feedstock shortages, and high production costs. On the other hand an additional benefit of SAF production technologies is that they often generate low-carbon co-products, like renewable diesel or gasoline, which can definitely be useful for other Applications. To meet the EU's climate targets, it will be essential to diversify both feedstocks and production methods: relying on a single pathway or raw material simply isn't sustainable on the long term.

Currently, SAF is mostly used in blends with fossil-based jet fuel, but the ultimate goal is clearly that of enabling the use of pure SAF: a great research effort is currently being made to overcome blending limits and certify SAF for use in its pure form. A success in this sense is key to reduce aviation's dependency on fossil fuels and satisfy the rising demand for more sustainable air transport.

The table below (Table 2) provides a summary of each SAF production pathway, including the main feedstocks used, the corresponding certification name, and the maximum allowable SAF blending ratio currently allowed.

Production pathways	Feedstocks	Certification name (bending limit)	Maximum SAF share
Biomass Gasification + Fischer-Tropsch (Gas+FT)	Energy crops, lignocellulosic biomass, solid waste	FT-SPK	50%
Hydroprocessed Esters and Fatty Acids (HEFA)	Vegetable and animal fat	HEFA-SPK	50%
Direct Sugars to Hydrocarbons (DSHC)	Conventional sugars, lignocellulosic sugars	HFS-SIP	10%
Biomass Gasification + FT with Aromatics	Energy crops, lignocellulosic biomass, solid waste	FT-SPK/A	50%
Alcohols to Jet (AtJ)	Sugar, starch crops, lignocellulosic biomass	ATJ-SPK	50%
Catalytic Hydrothermolysis Jet (CHJ)	Vegetable and animal fat	CHJ or CH-SK	50%
HEFA from algae	Microalgae oils	HC-HEFA-SPK	10%
ATJ with aromatics	Sugar, starch crops, lignocellulosic biomass	ATJ-SKA	50%
FOG Co-processing	Fats, oils and greases	FOG	5%
FT Co-processing	Fischer-Tropsch (FT) biocrude	FT	5%
Hydropocessed Lipids Co-processing	Hydroprocessed vegetagle oils, animal fats, used cooking oils	Hydroprocessed Lipids Co-proccessing	10%

Table 2 – Drop-in SAF qualified production pathways [4]

3.3. Environmental Benefits and Challenges of Sustainable Aviation Fuels [4] [5]

While the combustion of Sustainable Aviation Fuels (SAF) produces emissions similar to those of conventional fossil-based jet fuels, the total life cycle emissions are significantly lower. Much of the emissions reduction comes from using cleaner production methods and feedstocks that have a smaller environmental footprint. To evaluate the overall environmental impact of SAF, experts rely on Life Cycle Analysis (LCA), which evaluates emissions from feedstock cultivation, fuel production, and fuel combustion. GHG emissions are typically expressed in grams of CO2-equivalent per megajoule (gCO2e/MJ) of energy. As highlighted earlier, the potential for GHG reduction varies depending on the feedstock and production method. For example, fully decarbonized Power-to-Liquid (PtL) fuels can theoretically reduce net emissions by up to 100%. %. Beyond GHG, SAF production offers additional environmental benefits. As the feedstocks and production methods used typically contain lower levels of sulphur and aromatics, SAF combustion releases less particulate matter (PM), a key advantage, especially for areas near airports. There's also growing evidence that SAF can reduce contrail formation, whit a positive impact on atmospheric warming.

At the same time, technical limitations still pose challenges: one issue is that SAF tends to lack aromatic hydrocarbons, which are important for maintaining compatibility with nitrile rubber components in aircraft fuel systems. To guarantee material compatibility, SAF must meet a minimum aromatic content, which currently makes the use of 100% SAF blends more complex without the addition of approved aromatic compounds.

Even though the environmental benefits of SAF are clear, it is also important to consider the wider ecological and social impacts associated with their production. One of the major concern is land use: producing biofuel feedstocks can impact ecosystems and affect food supply. There are two main types of land use changes to be aware of:

- Direct Land Use Change (DLUC): when natural land is converted to grow feedstocks;
- Indirect Land Use Change (ILUC): when existing agricultural land is redirected towards biofuel production, displacing food production and potentially pushing it onto previously untouched land like forests or grasslands.

These land use changes might cancel out the GHG emission cuts, or worse, increase CO2-equivalent emissions. To deal with these risks, the European Union's Renewable Energy Directive II (RED II) restricts biofuels derived from food and feed crops, favoring waste oils and residues instead. Further, the 2023 update to RED made the rules even stricter, placing more focus on protecting biodiversity and limiting high-risk materials like palm oil and soy.

The Figure 13 provides an overview of the different production pathways for Sustainable Aviation Fuel, highlighting both the types of feedstock used and the associated life-cycle CO_2 emissions.

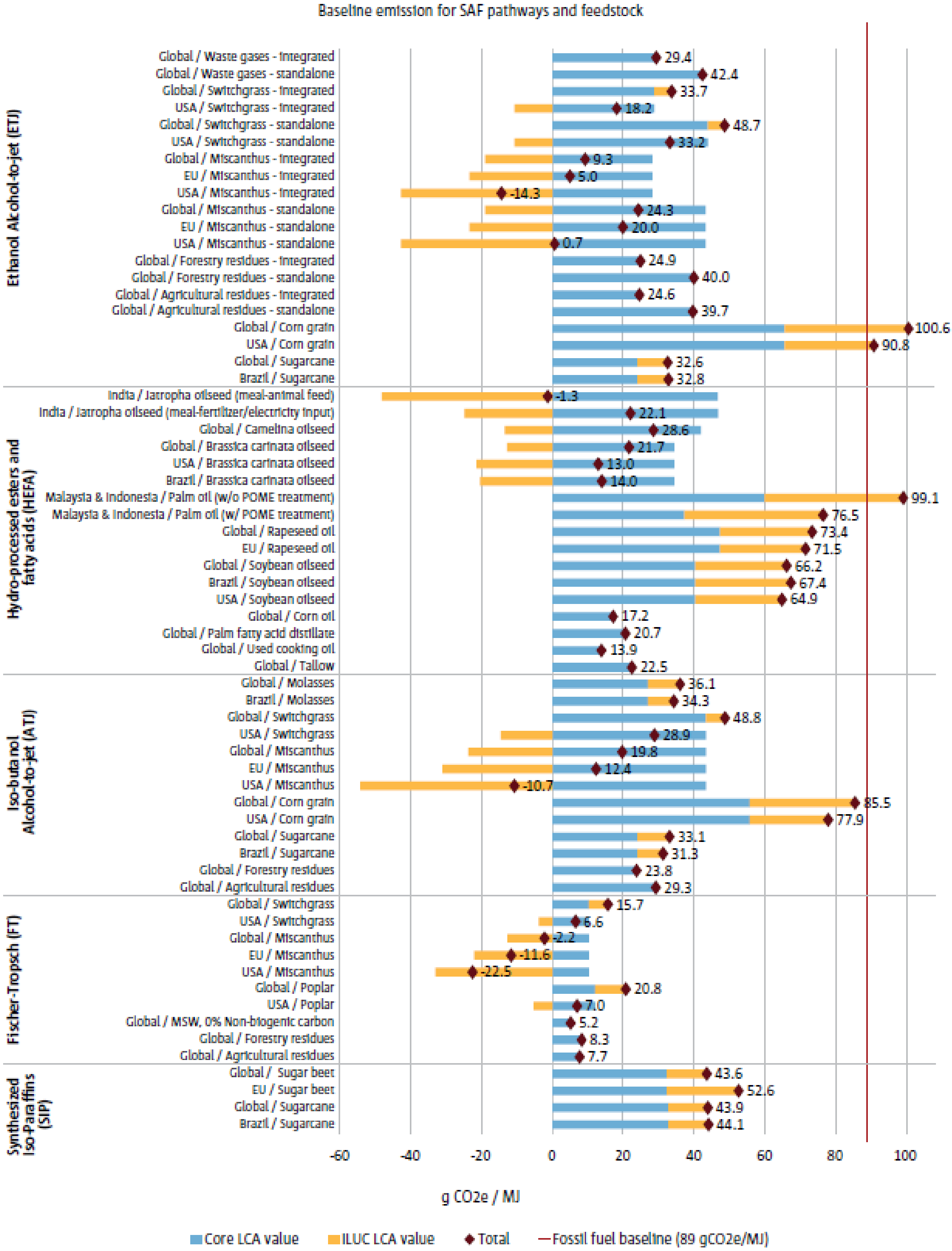


Figure 13 - LCA emissions reduction for CORSIA eligible SAF pathways and feedstock compared to a fossil fuel reference value (89 g CO2e/MJ) [4]

3.4. Policy actions supporting Sustainable Aviation Fuels [4] [6] [18] [20]

Sustainable Aviation Fuels play a key role in cutting greenhouse gas emissions according to global aviation policies. The European Union, through its ReFuelEU Aviation initiative, has introduced a set of ambitious targets to increase SAF use. Since 2025, airlines must use at least the 2% of SAF in their fuel mix, a minimum requirement that will rise to 6% by 2030 and climb steadily to reach 70% by 2050. Synthetic fuels also have specific targets associated: a minimum of 1.2% will be required in 2030, increasing to the 35% by mid-century. These regulations apply to all flights departing from EU airports above certain traffic thresholds, aiming to drastically cut carbon emissions from the aviation sector. Figure 14 provides an overview of the key points just discussed.

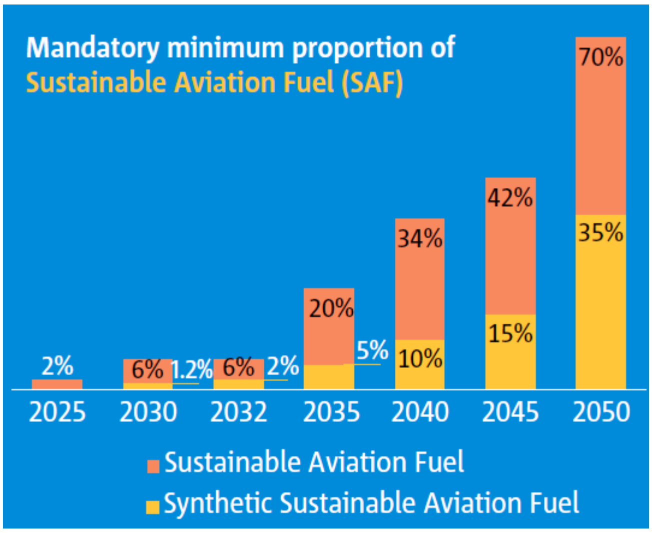


Figure 14 - Proposed "Fit for 55" SAF mandate [4]

To support this transition, the EU has introduced dedicated financial incentives. Airlines and fuel suppliers can benefit from zero-emission credits under the EU Emissions Trading System (ETS), while programs like Horizon Europe are investing on innovation and scaling up production. There are also penalties for falling short, and progress is closely monitored so that regulations can be adjusted when needed.

Individual countries are also introducing SAF policies: Norway introduced a SAF blending mandate starting with a 0.5% in 2022 with plans to increase it gradually. Sweden has gone further, setting a 27% SAF blend requirement in 2030.

Outside Europe, the EU fosters international partnerships with countries in Africa, Asia, Latin America, the Caribbean, and collaborating with global organizations like the International Civil Aviation Organization (ICAO) to build a worldwide framework for SAF adoption.

In the U.S., the government is aiming to produce 3 billion gallons of SAF by 2030, ramp that up to 17 billion by 2040, and eventually reach a capacity of 35 billion gallons by 2050. To help reaching this goal, $1 billion in incentives was allocated to grow SAF production infrastructure. Meanwhile, China's current five-year plan includes specific steps to cut aviation emissions by 4.5% by 2025, with a strong push for SAF development.

Despite these initiatives, the SAF market is still in its early phases: in 2024, SAF only accounted for about 0.53% of the total global jet fuel supply. In the EU, current production is just over 1 million tonnes per year, and nearly all of that comes from the HEFA pathway: this is what is considered as "operating scenario" in Figure 15. The figure also shows a "realistic scenario", in which SAF production could reach 3.5 Mt by 2030, assuming all facilities currently under construction become operational. This production level would be sufficient to meet the projected demand considering the mandatory 6% required by ReFuelEU by that same year (approximately 2.8 Mt). However, fulfilling the far more ambitious ReFuelEU requirement of a minimum of 20% SAF set for the 2030–2035 period will require a substantial scale-up in production capacity. In this realistic outlook, production is expected to be almost entirely based on the HEFA pathway, as no Power-to-Liquid (PtL) plants have so far progressed beyond the pilot stage. Last, the "optimistic scenario" assumes that all planned SAF projects, including those using Power-to-Liquid (PtL) technologies, will be up and running by 2030. According to estimates from ReFuelEU Aviation and SkyNRG, this could bring total production capacity to around 5.5 to 5.6 million tonnes.

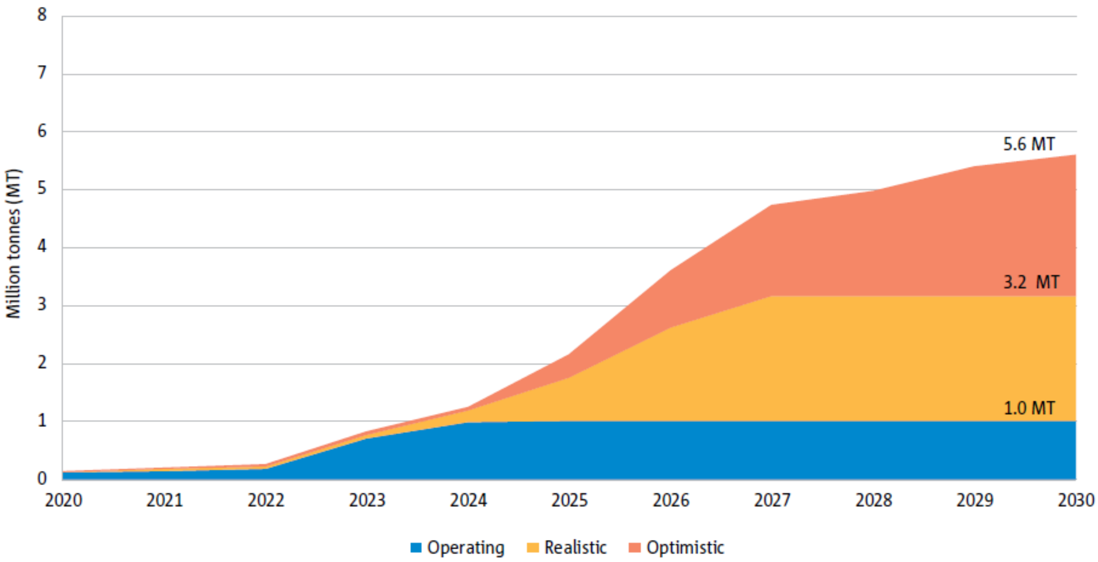


Figure 15 - Projected EU+EFTA SAF capacity in 2030 by scenario [4]

As discussed above, fuels produced in HEFA/HVO refineries is not solely Sustainable Aviation Fuel, but a liquid hydrocarbon blend of which SAF only represents a portion. Currently, it's often more profitable for these refineries to sell all liquid products as renewable diesel rather than separating out the SAF fraction. Still, if all existing HEFA production facilities invested in extra infrastructure to split the liquid product into two separate fractions, SAF and biodiesel, it is estimated that up to a billion extra litres of SAF could be produced. That shift could raise the SAF fraction of the HEFA processes' output from roughly the 15% to a percentage up to the 50%. On the downside, the added processing steps would make production more expensive, especially due to increased hydrogen use.

Looking ahead, scaling up production is going to be a major challenge. To meet its climate targets, the EU will need around seven new SAF plants by 2030, and over 100 by 2050. To meet the growing demand for SAF, it will be crucial to expand the range of feedstocks beyond traditional vegetable oils. So far, vegetable oils like soy, rapeseed, and sunflower were the main inputs, but not without drawbacks, as high prices and potential conflicts with food supply. For this reason, research is shifting toward alternative feedstocks that don't compete with agriculture: among the most promising are lignocellulosic residues from farming and forestry, algae, sludge, and even waste gases from industry. These sources not only avoid competition with food crops but also offer the potential for greater sustainability and further carbon emissions reduction.

3.5. Market Mechanisms and the future of Sustainable Aviation Fuels [4] [21] [22]

While Sustainable Aviation Fuels hold significant potential for reducing emissions in the aviation sector, their relatively high cost still remains a significant barrier to widespread adoption. Currently, SAF prices range is from 1.5 to 6 times higher than conventional fossil-based jet fuel. This price gap is primarily due to the early stage of commercial deployment, limited production scale, and feedstock availability constraints. However, as production technologies mature and economies of scale are implemented, the cost of SAF is expected to decline substantially, making SAF a more affordable option over time.

Fuel expenses typically represent the 30% of an airline's operating costs, making the price of SAF a critical factor for their adoption. Back in 2023, conventional jet fuel was priced at approximately €816 per tonne according to the Price Reporting Agency (PRA) indices, while aviation biofuels averaged €2768 per tonne.

For SAF pathways not yet commercially available, production cost has been estimated to range from €1600 per tonne for advanced biofuels to €8700 per tonne for Power-to-Liquid (PtL) fuels. This wide range reflects the different production routes and technologies, some of which are capable of reducing lifecycle emissions by over 90% compared to fossil-based jet fuel. Figure 16 illustrates these cost differences across fuel types, highlighting both the current market prices and the projected production costs for emerging SAF technologies.

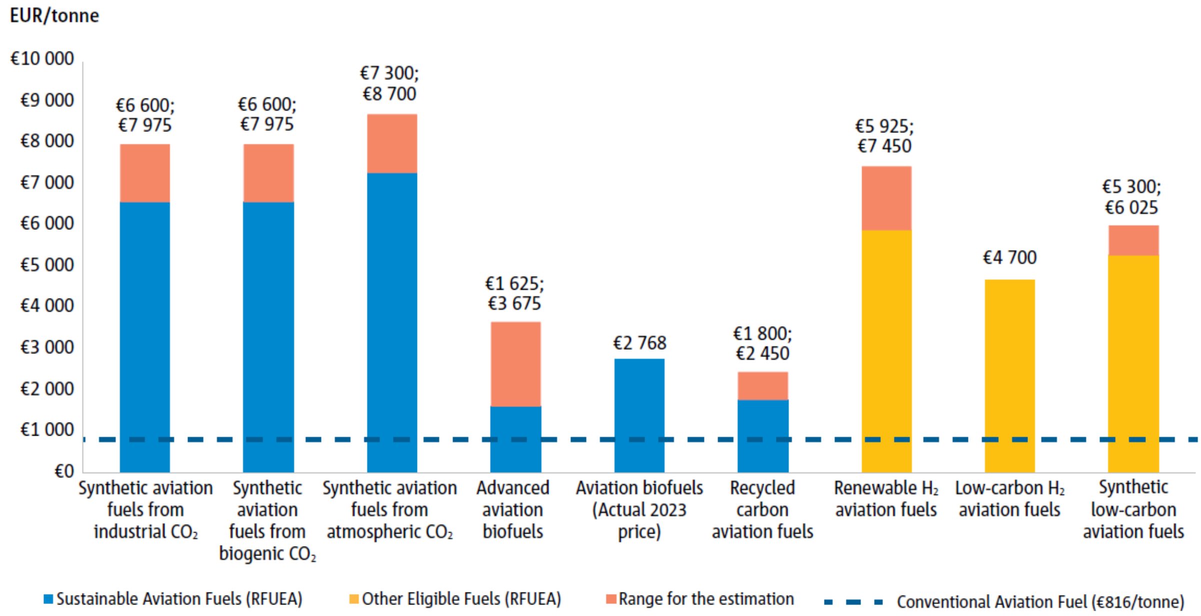


Figure 16 - Estimated prices and production costs in 2023 for ReFuelEU Aviation eligible fuels [4]

A 2020 review of minimum selling prices (MSP) for different SAF production methods revealed some wide cost differences. As shown in Figure 17, HEFA, which is currently the most commercially mature pathway, had an average MSP of €1.21 per litre. On the opposite end, electrofuels, produced via PtL processes, were the most expensive at €2.99 per litre. In between were the AtJ and FT pathways, with MSPs of €1.81 and €1.91 per litre respectively. These values reflect production costs at early commercial or pilot scale. Over time, prices are expected to decrease significantly, particularly for electrofuels, as the cost of renewable electricity and electrolyzer technologies declines. HEFA, despite its relatively low cost, faces feedstock availability constraints that could limit its scalability on the long term. On the other hand, FT and AtJ routes offer more flexibility in feedstock use and are likely to obtain greater benefit from economies of scale.

Looking further ahead, projections indicate that SAF prices could converge with those of conventional jet fuel by 2050. That's assuming continued advances in technology, strong policy support, and wider adoption. Several studies even predict cost cuts of up to 50% for certain pathways by mid-century, driven by better infrastructure and improved process efficiency, enhancing long-term competitiveness.

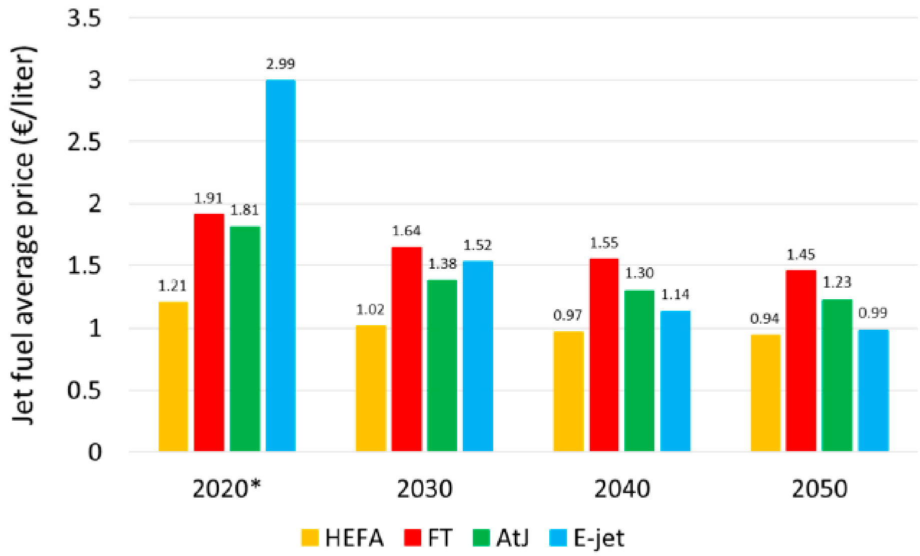


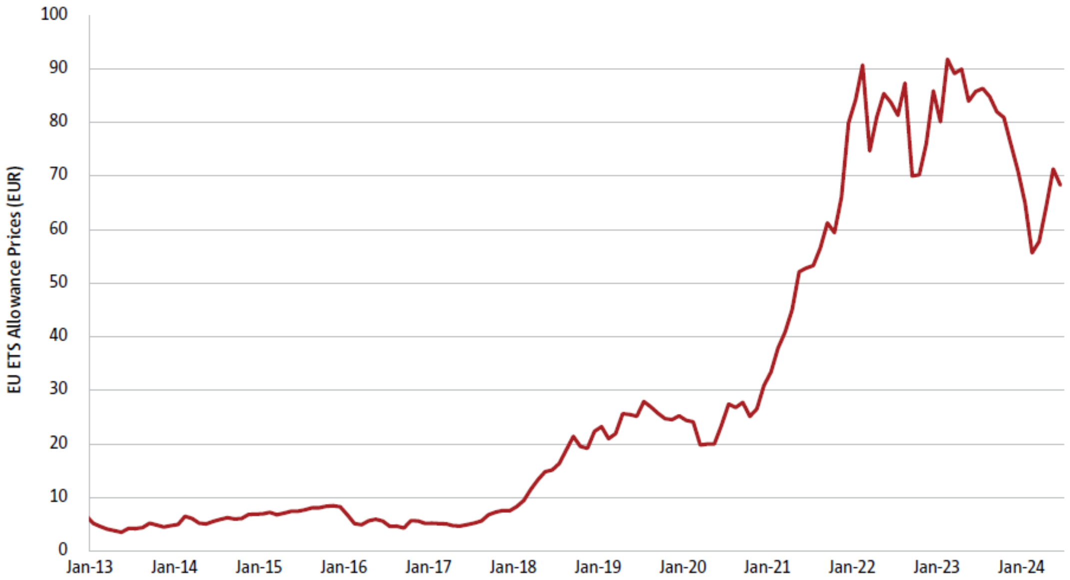
Figure 17 - Jet fuel average price (€/litre) [22]

Market-based instruments play a key role in bridging the cost gap so to incentivize SAF adoption. For this purpose, one of the main tools currently available is the European Union Emissions Trading System (EU ETS), which plays a central role in the EU's climate strategy: its purpose is to let stakeholders trade CO_2 emission allowances across different sectors, helping to cut emissions where it's most cost-effective.

In 2012 the aviation sector was included in the EU ETS, though in the beginning it only applied to flights within the European Economic Area (EEA) with flights to and from non-EEA countries still temporarily excluded until the end of 2023. Since 2024, the ETS system applies to flights within the EEA, including those to Switzerland and the United Kingdom. For flights outside this area, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) comes into play, the reader will be provided with more information about this topic in the next section.

To further encourage airlines to use SAF use, the EU is making up to 20 million ETS allowances available from 2024 to 2030 for carriers that include sustainable fuels in their mix. This measure aims to reduce the price difference between SAF and fossil kerosene, making sustainable fuels more economically attractive.

As post-pandemic emissions rebound, aviation emissions have started climbing again. Verified CO_2 emissions from aviation reached 53.0 million tonnes in 2023 and the aviation sector has once again became a major purchaser of EU Allowances (EUA), with emissions projected to increase to 59.5 Mt in 2026. As a result, the cost associated with the EU ETS for aviation has risen, with prices exceeding €90 per tonne of CO_2 in 2022 and 2023. Estimations suggest that ETS cost could account for 4% to 6% of airlines' total annual operating expenses by 2024. The following figure (Figure 18) shows the trend in ETS prices over the years.



3 Estimation from EASA AERO-MS model. See Appendix C for more details.
4 Estimation from EASA AERO-MS model.

Figure 18 - EU ETS Allowance Prices (2013-2024) [4]

The EU ETS is linked with Switzerland's emissions trading system, covering flights between the EEA and Switzerland. Similarly, the United Kingdom implemented its own ETS in 2021, which applies to flights between the UK and the EEA, ensuring continuity in carbon pricing mechanisms across Europe.

3.6. CORSIA: mechanisms, phases, and contributions to Sustainable Aviation [4] [5] [23] [24]

In 2016, the International Civil Aviation Organization (ICAO) adopted a global framework aimed at keeping under control CO_2 emissions from international flights. This led to the creation of the Carbon Offsetting and Reduction Scheme for International Aviation, better known as CORSIA. Its main goal is to compensate for any increase in emissions above 2020 levels, helping the aviation sector to enhance carbon-neutral growth.

CORSIA operates under ICAO's Standards and Recommended Practices (SARPs), which are regularly reviewed and updated to reflect evolving circumstances and scientific understanding. An important revision shifted the baseline for offsetting requirements from 2020 to 2019 emissions for the pilot phase (2021–2023). For the next stage (2024–2035), emissions offsetting is calculated considering the 85% of 2019 levels, so introducing a slight reduction to encourage further emissions mitigation.

The scheme applies to international flights between ICAO member states that both participate in CORSIA. Participation has expanded significantly, with 129 countries involved as of 2025, up from 88 in 2021. Starting in 2027, CORSIA will become mandatory for nearly all ICAO member states, hence substantially broadening its coverage. CORSIA targets airlines operating international flights emitting more than 10000 tonnes of CO_2 annually, operating aircrafts with a maximum take-off weight above 5700 kg. These operators will be required to monitor, report, and verify their emissions annually.

The figure below (Figure 19) shows which countries have joined the CORSIA program during its different phases.

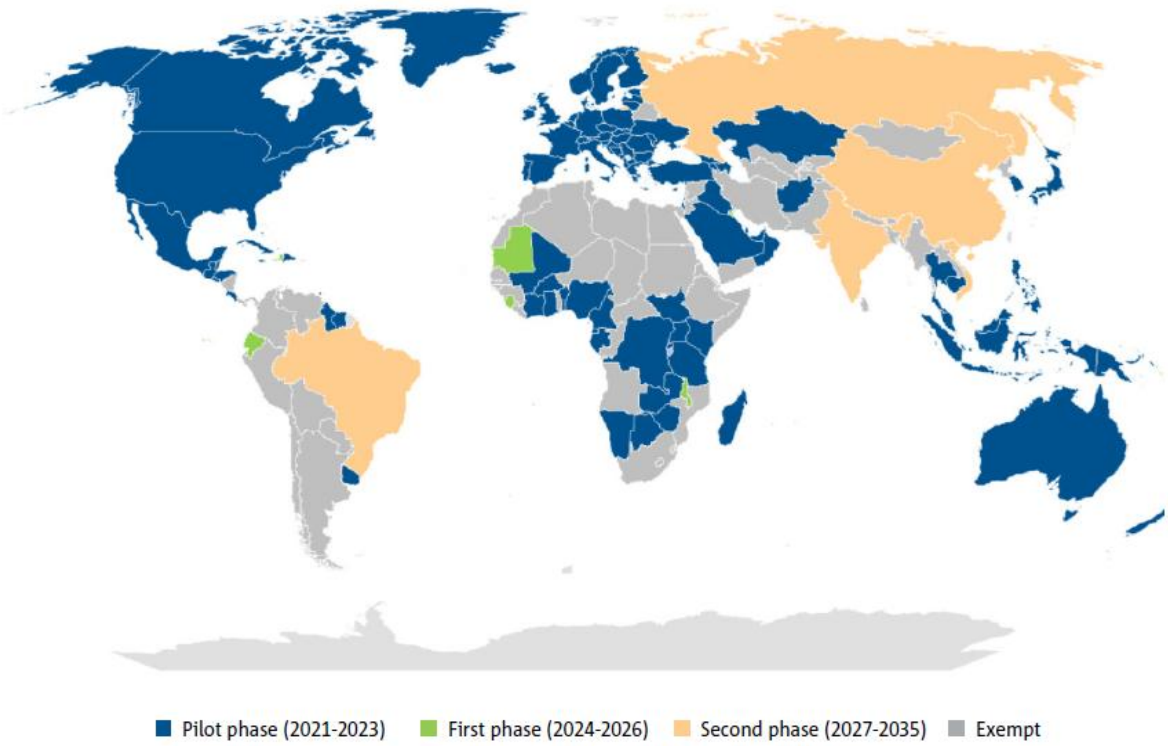


Figure 19 - ICAO Member States participation in CORSIA offsetting in various phases [4]

As mentioned above, CORSIA's implementation is divided into three phases:

- the pilot phase (2021–2023): voluntary participation with offsetting requirements applied only to flights between participating states;
- the first phase (2024–2026): continued voluntary participation with expanded offsetting obligations;
- the second phase (starting in 2027): mandatory participation for nearly all ICAO contracting states, with some exceptions.

To reduce aviation's environmental impact, CORSIA supports the use of Sustainable Aviation Fuels that meet specific sustainability criteria, including at least a 10% reduction in lifecycle CO_2 equivalent emissions compared to conventional fossil fuels. Additionally, CORSIA supports carbon removal projects, both natural (such as reforestation) and technological (such as direct air capture).

While CORSIA shares similarities with the EU Emissions Trading System (EU ETS) in terms of strict monitoring, reporting, and verification requirements, the two systems are structured differently. The EU ETS operates as a cap-and-trade system, setting an emissions cap and permitting trading of allowances within the European Economic Area. In contrast, CORSIA is an offsetting scheme designed to stabilize emissions growth globally by requiring airlines to purchase carbon credits for emissions exceeding the established baseline. Importantly, carbon credits from the EU ETS are not accepted under CORSIA, and vice versa, reflecting their distinct legal frameworks.

The EU ETS applies primarily to flights within the EEA, while CORSIA focuses on international flights between participating ICAO member states. Carbon credits under CORSIA finance projects that reduce or remove CO_2 emissions globally, such as renewable energy initiatives, forest conservation, and carbon capture technologies. To be eligible, these credits must meet strict requirements to ensure that the reductions are real and lasting.

As highlighted in Figure 20, during the pilot phase, CORSIA-eligible carbon credits are estimated to range between $18 and $51 per tonne of CO_2 equivalent, rising to a range between $27 and $91 in the successive phase. These rising prices are likely to affect airline costs and may lead to slight increases in ticket prices for international travel. This shift reflects how carbon markets are becoming a more important part of aviation's long-term climate strategy.

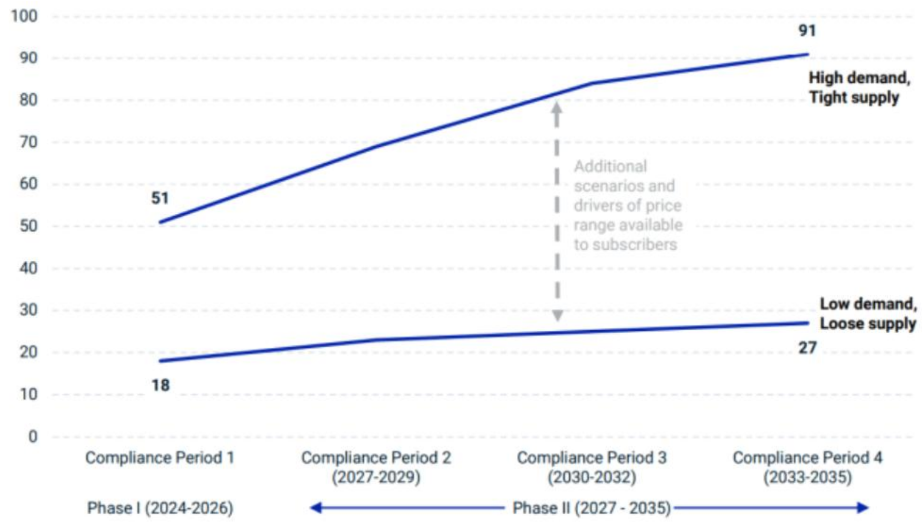


Figure 20 - CORSIA prices for: High demand, tight supply and Low demand, loose supply (USD per tCO2e) [24]

4. Assessing the impact of Sustainable Aviation Fuel across global airports [4] [25] [26]

To better understand the environmental benefits and economic implications associated with Sustainable Aviation Fuel adoption a case study is examined in this chapter. In order to provide the reader with a broad view, the provided case study focuses on five major international airports, each representing a different geographic region and operational context:

1. London - Heathrow Airport (LHR) [27]:

   LHR is the main international gateway serving London and the Europe's busiest airport for international passenger traffic. In 2024, it handled over 83 million passengers and recorded about 475000 aircraft movements. With more than 90 airlines operating from its terminals, Heathrow provides connections to over 230 destinations worldwide.

2. Rome Fiumicino - Leonardo da Vinci Airport (FCO) [28]:

   FCO is Italy's largest airport and a key hub in the Mediterranean region. In 2024, it handled around 49 million passengers and recorded approximately 315000 aircraft movements. FCO acts as a key link between Europe and North America, the Middle East, and other global regions.

3. New York - John F. Kennedy Airport (JFK) [29]:

   JFK is the main international airport serving New York City and one of the busiest airports in the United States. In 2024, JFK handled approximately 31 million passengers and 460000 aircraft movements. The airport is a central hub for many international airlines, offering extensive intercontinental connectivity across all continents.

4. São Paulo - Guarulhos Airport (GRU) [30]:

   GRU is Brazil's busiest airport and the largest in South America by passenger volume. In 2023, it served approximately 41 million passengers and recorded around 280000 aircraft movements. GRU represents a major hub for both domestic and international flights, playing a critical role in connecting Brazil with the Americas, Europe, and beyond.

5. Sydney - Kingsford Smith Airport (SYD) [31]:

   SYD is Australia's main international airport and the busiest in the country. In 2024, SYD handled about 41 million passengers with roughly 300000 aircraft movements. As the main gateway to Australia, Sydney Airport connects the country to major global destinations and serves as a central hub for domestic flights.

These airports were selected to provide a representative spectrum of different regional characteristics, reflecting diverse market dynamics and regulatory environments. The purpose is to highlight how SAF adoption can vary widely depending on factors like flight volume, route types, and regional policies. Notably, no Asian airport is included in this analysis due to the limited availability of reliable data for the region.

In mature markets such as the United States and Europe, characterized by large hub airports and extensive long-haul networks, SAF deployment offers substantial opportunities to reduce overall aviation emissions. These regions also benefit from robust regulatory frameworks and financial incentives that actively promote SAF production and use.

Conversely, emerging and expanding aviation markets such as Brazil and Australia provide an example for the evolving role of SAF in expanding aviation markets. Brazil, for example, with its rich agricultural resources and developing SAF industry, is particularly well-positioned to become a leading producer of SAF, especially through bio-based pathways like Alcohol-to-Jet and Fischer-Tropsch processes.

This regional perspective highlights how local factors, such as feedstock availability, policy support, and market demand, shape the pace and scale of SAF deployment. Recognizing these differences is crucial when designing strategies to promote SAF adoption in ways that maximize the positive environmental impact while balancing economic and operational needs.

In brief, the goal of this case study is to highlight both the climate benefits of SAF and the economic implications for airlines operating at these key airports. Such insights are vital for policymakers, airport authorities, and industry stakeholders seeking to formulate effective, region-specific strategies to accelerate the global deployment of Sustainable Aviation Fuels.

4.1. CO_2 emissions calculation [32]

For each one of the previously identified airports, a selection of representative medium-range flight routes was considered (see Figures 22-26 for more details). The CO_2 emissions associated with each route were calculated through the ICAO Carbon Emissions Calculator (ICEC) (see Tables 3-7).

The ICAO Carbon Emissions Calculator (ICEC) uses an internationally recognized methodology to estimate the carbon dioxide (CO_2) emissions per passenger for a given flight, with the primary aim of supporting carbon offset programs. This approach relies on a distance-based calculation combined with industry-average data on aircraft types, fuel consumption, passenger load factors, and cargo proportions. By inputting the origin and destination airports of a flight, the calculator identifies the typical aircraft type serving that route and estimates fuel consumption based on the Great Circle Distance. Then, by evaluating flight frequency and operational data, the fuel consumption per passengers is calculated and then converted into CO_2 emissions through a fixed emission factor.

To better understand how the ICEC operates, it is useful to examine the key inputs and calculation steps behind the methodology (summarized in Figure 21).

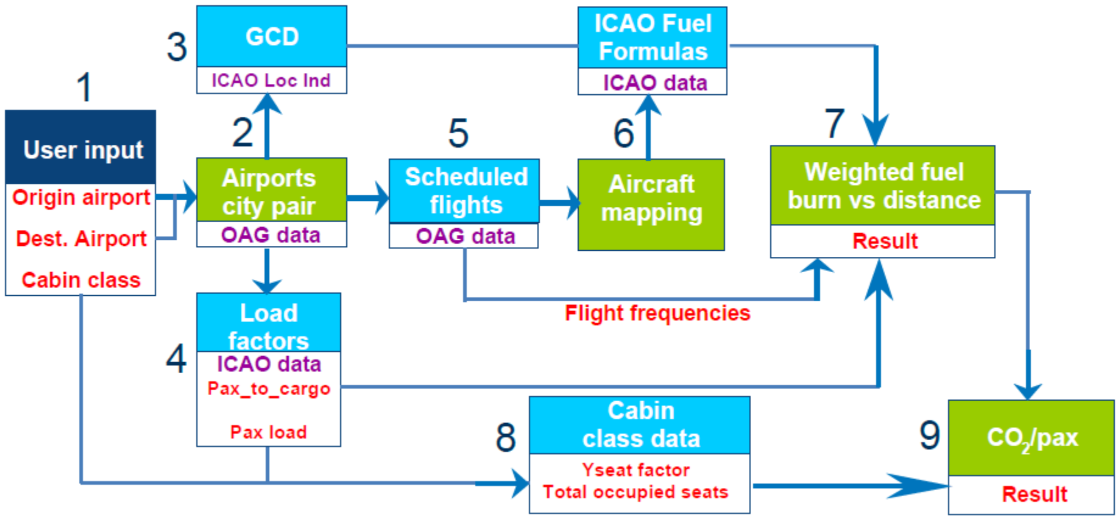


Figure 21 - The methodology adopted by ICEC [32]

User input (1) – The user enters the origin and destination airports and selects the cabin class (economy, premium economy, business, or first). The calculator searches for all flights serving that city pair, including those with one or more stops. The cabin class selection is required because this calculator provides as a result an average emissions-per-passenger value. It is hence necessary to consider the different amount of on board space taken by passengers flying in different classes.

City Pair (2) & Scheduled flights (5) – Flight schedule data and city-pair information are sourced from the Official Airline Guide (OAG), which provides up-to-date global airline schedules updated every two months.

GCD (3) – Using airport coordinates from the ICAO Location Indicators database, the Great Circle Distance (GCD) between origin and destination is calculated and adjusted by a correction factor based on route length to better reflect actual flight paths.

Load Factors (4) – Passenger load factors and passenger-to-cargo ratios are assigned to each city pair based on route groups covering international, domestic, and regional flights. These values come from ICAO's Traffic by Flight Stage database, which compiles annual traffic and operational data by aircraft type and route.

Aircraft Mapping (6) – Scheduled aircraft from the OAG database are matched to ICAO's fuel consumption database by means of the Fuel Consumption Formula. If a specific aircraft is not listed, calculation are carried out upon data of one of 336 listed aircraft types through analogy.

Weighted Fuel Burn vs Distance (7) – Fuel burn (kg) is estimated upon flight distance (km) by means of ICAO's Fuel Consumption Formula, which accounts for passenger load factor, passenger-to-cargo ratio, flight distance, block hours, and aircraft types. The total fuel used on a route is calculated as a weighted average considering the share of flights carried out by each aircraft type.

Cabin Class Data (8) – The user's selected cabin class (economy, premium economy, business, or first) is considered so to adjusts the amount of fuel burnt per passenger through a "Yseat" factor. This so to reflect the relative space occupied by seats in different classes to rectify the CO_2 emissions accordingly. The "Yseat" factor is defined as the ratio between the surface area of a specific seat and the minimum seat surface (usually economy class) on the same aircraft and airline. It is important to point out that in this analysis only economy class seats were considered.

For this study case, the routes were chosen so to represent real flights currently operated, ensuring that the analysis reflects real-world conditions. Once the departure and arrival airports for each route are entered into the ICAO Carbon Emissions Calculator (ICEC), the tool provides significant statistics for each pair of departure and destination cities, including the flight distance, the amount of fuel burned, and the CO2 emissions. The detailed output data generated by ICEC is reported in the Appendix A for ease of reference.

Considering real operational routes enhances the accuracy and relevance of the case study, offering a clearer picture of the current emissions profile of medium-range flights, shedding light on how current operations contribute to the sector's carbon footprint and hence providing a realistic environmental impact assessment. This is essential to evaluate the potential role of Sustainable Aviation Fuels and other mitigation measures in reducing the carbon footprint of aviation. Moreover, this data can serve as a foundation for policymakers, airport authorities, and airline operators to identify those routes for which the deployment of SAF could generate environmental benefits more effectively.

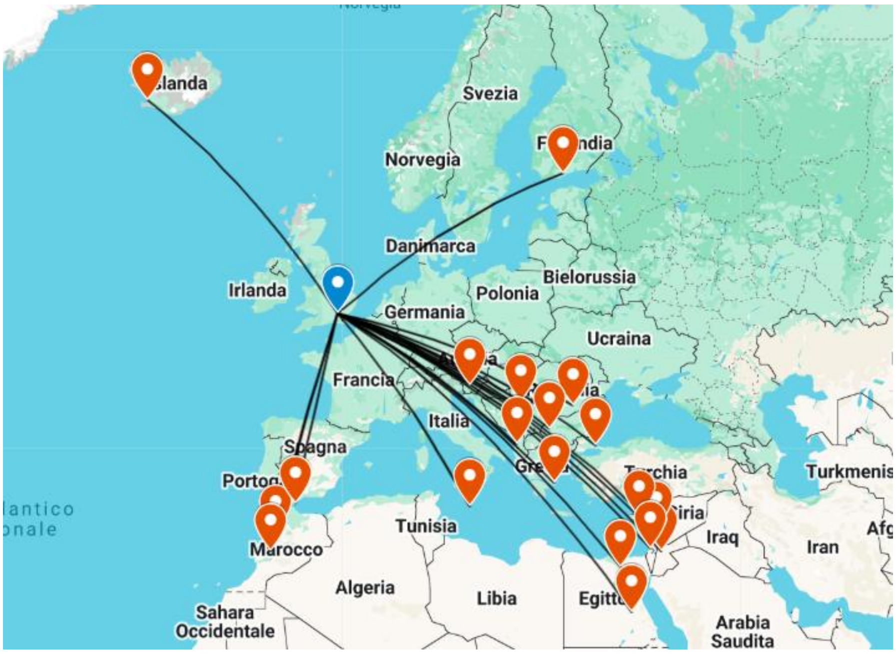


Figure 22 - Medium range routes from London (LHR) [33]

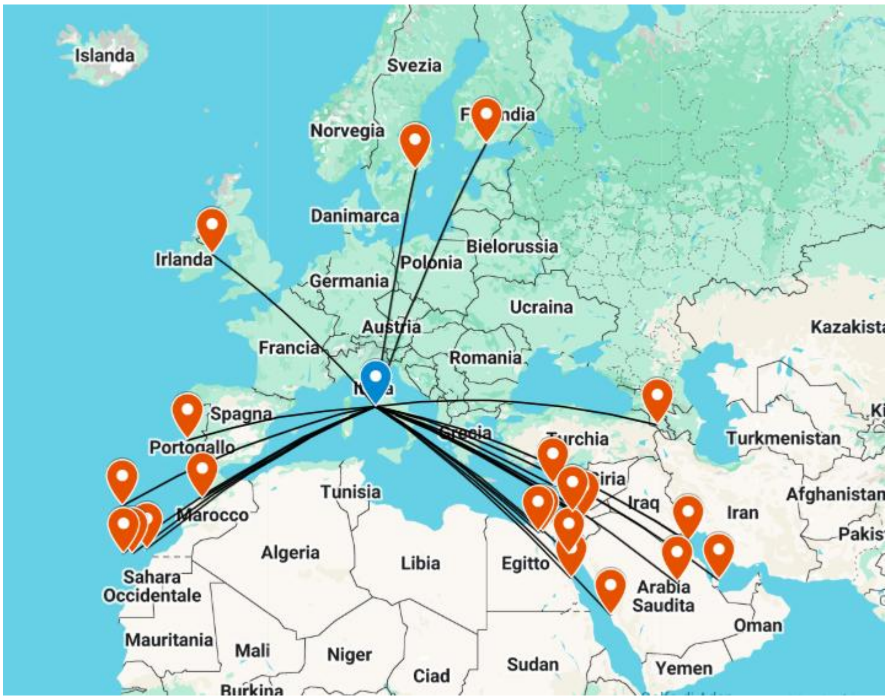


Figure 23 - Medium range routes from Rome (FCO) [33]

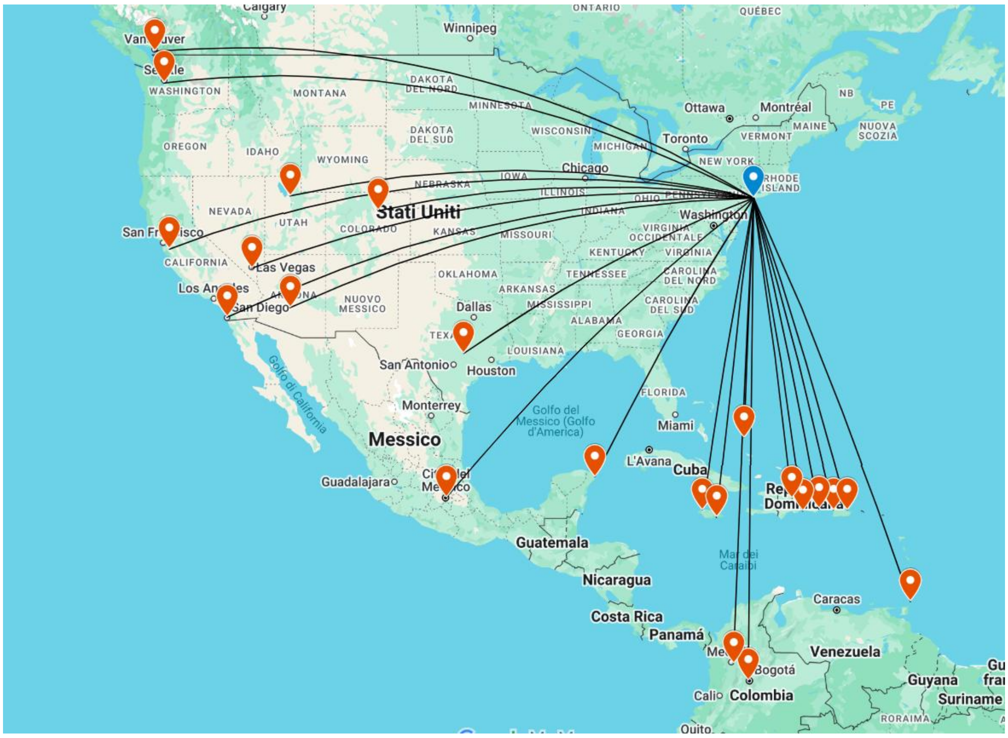


Figure 24 - Medium range routes from New York (JFK) [33]

Figure 25 - Medium range routes from Sao Paulo (GRU) [33]

Figure 26 - Medium range routes from Sydney (SYD) [33]

4.2. Evaluating emission benefits and costs of Sustainable Aviation Fuels across different regions [4] [34]

To evaluate the environmental benefits and economic consequences associated to the use of Sustainable Aviation Fuels and to identify the most promising areas for investment, a targeted selection of SAF producers was identified across each key geographic region. Then, for each selected producer, the production methods and feedstock inputs were closely examined. This detailed evaluation was carried out so to enable an approximate estimation of the greenhouse gas emissions and production costs for each one of the considered producers, hence allowing a realistic comparison with conventional Jet A-1 fuel considering the complete lifecycle.

First, an extensive search process was carried out so to obtain the data summarized in Table 3: for each airport the main current SAF suppliers were identified, what can be noticed is that the majority of the producers considered are established refineries with experience in the fossil fuel industry. Further, additional information was retrieved, regarding the production method, the feedstock and the production facility location.

Airport	*Company*	*Facility Location*	*Production Method*	*Feedstock*
London Heathrow (LHR)	Shell [35]	Rhein-Ruhr Refinery: Wesseling, Germany	HEFA, Alcohol-to-Jet (ATJ)	Waste oils
	Shell [35]	Pernis Refinery: Rotterdam, Netherlands	HEFA, Alcohol-to-Jet (ATJ)	Waste oils
	ST1 [36]	Gothenburg, Sweden	Technology not specified	Used cooking oil, animal fats, tall oil fatty acids
	Nordic Blue Crude [37]	Stavanger, Norway	Fischer-Tropsch + RWGS	CO2, hydrogen
	Preem [38]	Gothenburg, Sweden	Technology not specified	Used cooking oil, waste tallow, rape seed oil
	Velocys [39]	Immingham, United Kingdom	Fischer-Tropsch	Municipal and commercial solid waste
	LanzaTech [40] [41]	Scotland	Gas fermentation + Alcohol-to-Jet (ATJ)	Waste gases
	LanzaTech [40] [41]	Belgium	Gas fermentation + Alcohol-to-Jet (ATJ)	Waste gases
	TotalEnergies [42] [43]	Normandy Refinery, France	Methanol-to-Jet (ATJ-SPK)	Methanol (for ATJ-SPK project)
Rome-Fiumicino (FCO)	Eni [44]	Gela Refinery: Gela, Sicily, Italy	Ecofining™ (Hydrotreating)	Used cooking oil, residues from agri-food industry
	Eni [44]	Venice Refinery: Porto Marghera, Venice, Italy	Ecofining™ (Hydrotreating)	Used cooking oil, residues from agri-food industry
	Cepsa [45] [46]	Huelva Refinery: Huelva, Andalusia, Spain	Not specified	Used cooking oils

	Bio-Oils [46]	Huelva, Andalusia, Spain	Not specified	Agricultural residues, used cooking oils
	Apical [47]	Huelva, Andalusia, Spain	Not specified	Agricultural residues, used cooking oils
	REPSOL [48]	Cartagena, Spain	Technology not specified	Waste oils
	Hellenic Petroleum [49]	Greece (generic facility)	Not specified	Not specified
New York-JFK (JFK)	World Energy [50]	Paramount, California, USA	HEFA	Inedible agricultural waste, fats, oils, and greases
	World Energy [50]	Houston, Texas, USA	HEFA	Inedible agricultural waste, fats, oils, and greases
	Gevo [51]	Luverne, Minnesota, USA	Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK)	Sustainable corn, cellulosic feedstocks
	Gevo [51]	Silsbee, Texas, USA	Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK)	Sustainable corn, cellulosic feedstocks
	Gevo [51]	Indianapolis, Indiana, USA	Alcohol-to-Jet Synthetic Paraffinic Kerosene (ATJ-SPK)	Sustainable corn, cellulosic feedstocks
	Honeywell UOP [52]	Des Plaines, Illinois, USA	Fischer-Tropsch Unicracking™	Wood waste, food scraps
	Honeywell UOP [52]	Houston, Texas, USA	Fischer-Tropsch Unicracking™	Wood waste, food scraps
	Fulcrum Bioenergy [53]	Reno, Nevada, USA	Fischer-Tropsch	Residual waste (landfill waste)
Sao Paulo-Guarulhos (GRU)	Petrobras [54]	Brazil	Alcohol-to-Jet (ATJ)	Corn, cane ethanol

	GranBio [55]	Brazil	Not specified	Wood chips, sugar cane residue
Sydney (SYD)	AmericanAgEnergy [56]	Australia	Biomass gasification	Wood, straw, bagasse, nut shells, rice hulls, oat hulls
	LanzaTech [40] [41]	New Zealand	Gas fermentation + Alcohol-to-Jet (ATJ)	Biomass
	NZ Biofuels [21]	New Zealand	Not specified	Biomass, algae

Table 3 - Overview of SAF production facilities, technologies and feedstocks associated with selected airports

After collecting all the necessary information, it was eventually possible to calculate the emissions in grams of CO_2 equivalent per megajoule (gCO_2eq/MJ) associated to SAF production for every airport examined.

The data provided in Table 3 were combined with those from Figure 13 (see page 45) that provide average emissions values for each production process. The calculation was carried out assuming the share of SAF provided to an airport by each of its supplying facility to be the same and, similarly, that each producer relied upon different feedstock sources equally. This simplification was necessary due to the lack of reliable sources from which to gather more detailed information, but still it doesn't prevent us from reaching realistic and useful results.

The results of this assessment are summarized in Table 4. The significant differences between different airports point out how the type of feedstock and the production technology used can deeply affect emissions associated with SAF production. For a better understanding, Figure 27 offers a visual representation of the table's data, including a comparison with the standard emission profile of Jet A-1 fuel.

Airports	***Emissions [gCO2eq/MJ]***
London Heathrow (LHR)	21.3354
Rome Fiumicino (FCO)	19.5133

New York (JFK)	24.5383
Sao Paulo (GRU)	44.4800
Sydney (SYD)	23.6366

Table 4 - Emissions (gCO_2eq/MJ) for SAF at selected airports

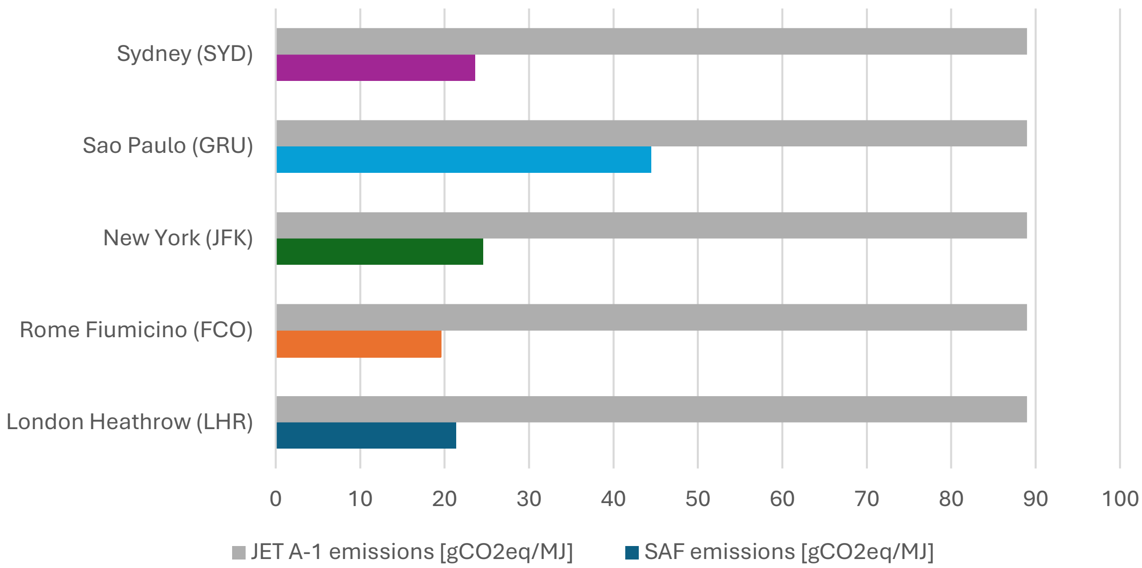


Figure 27 - Emissions (gCO_2eq/MJ) for SAF and Jet A-1 at selected airports

This comparative analysis clearly underscores that non all SAF options are equal, as their environmental impacts and cost-efficiency can vary widely and the difference can be remarkable. As the industry looks to scale up SAF deployment, directing investment toward the most sustainable and efficient production methods is not just advisable, but essential for achieving meaningful emissions reductions without compromising economic feasibility.

Besides CO_2 emissions, the economic impact shall also be considered and hence this analysis also focuses on comparing the cost of different SAF blends and conventional Jet A-1 fuel. This comparison was made for the present year as well as for 2030 and 2050, accounting for the EU's ReFuelEU Aviation program requirements about SAF blend percentages and also costs variation over time.

The cost evolution trends for Jet A-1 are presented in Table 5, while Figure 17 (see page 51) illustrates the cost projections for various SAF production methods.

	Annual Growth
2024-2034	+ 0.90 %
2024-2044	+ 1.00 %

Table 5 – Annual Growth of Jet Fuel Price [57]

Currently, Jet A-1 price fluctuates between approximately €0.57 and €0.61 per litre, whereas SAF remain significantly more expensive, often ranging from two to seven times that conventional jet fuel, depending on production pathways and specific feedstocks used. Despite this price gap, projections for 2030 and 2050 suggest a notable reduction in SAF costs. This downward trend is expected to result from advances in technology, greater production scale, and policy support through mechanisms like the EU Emissions Trading System (ETS) and financial incentives under ReFuelEU: instruments designed to narrow the price gap by rewarding low-carbon fuels and penalizing fossil emissions. The aim is to strengthen the economic case for SAF as, according to industry analysts, when carbon pricing and full lifecycle emissions are taken into account, SAF begins to emerge as a far more competitive and compelling alternative to conventional jet fuel.

Beginning with data from Table 3 and once again assuming that each airport is supplied by all production facilities in equal share, it was possible to estimate the cost of each "local" SAF blend and it's evolution over time by interpolating and averaging data provided by Figure 17 (see page 51).

Table 6 illustrates the projected variation of aviation fuels prices across five major international airports from 2025 to 2050. The data shows that Sustainable Aviation Fuels are significantly more costly than conventional Jet A-1 fuel in all regions. Notably, SAF prices are expected to decline over time while Jet A-1 will get progressively more expensive, though the cost of the latter is projected to remain higher, at least until 2050.

The regional differences in SAF pricing reflect variations in feedstock availability, production technologies, and local market conditions. For example, airports in regions with established biofuel industries and access to cost-effective feedstocks, such as used cooking oil, animal fats, agricultural residues and municipal solid waste, may experience relatively lower SAF prices compared to others. Conversely, regions where SAF production relies on more expensive or less mature pathways tend to face higher costs.

Figure 28 considers the same data of Table 6, but its purpose is to give an immediate visual comparison of SAF prices across regions and against the price of Jet A-1 fuel price. To provide a single reference point the price of Jet A-1 considered in the figure is the global average, considering its very limited local fluctuations.

	SAF			***JET A-1***		
	2025	**2030**	**2050**	**2025**	**2030**	**2050**
London Heathrow (LHR)	1.48	1.31	1.17	0.59 [58]	0.62	0.68
Rome-Fiumicino (FCO)	1.27	1.13	1.03	0.59 [58]	0.62	0.68
New York-JFK (JFK)	1.56	1.39	1.24	0.60 [58]	0.63	0.69
Sao Paulo-Guarulhos (GRU)	1.63	1.38	1.23	0.61 [58]	0.64	0.70
Sydney (SYD)	1.68	1.51	1.22	0.57 [58]	0.60	0.66

Table 6 - Variation in Aviation Fuel Prices [€/litre]

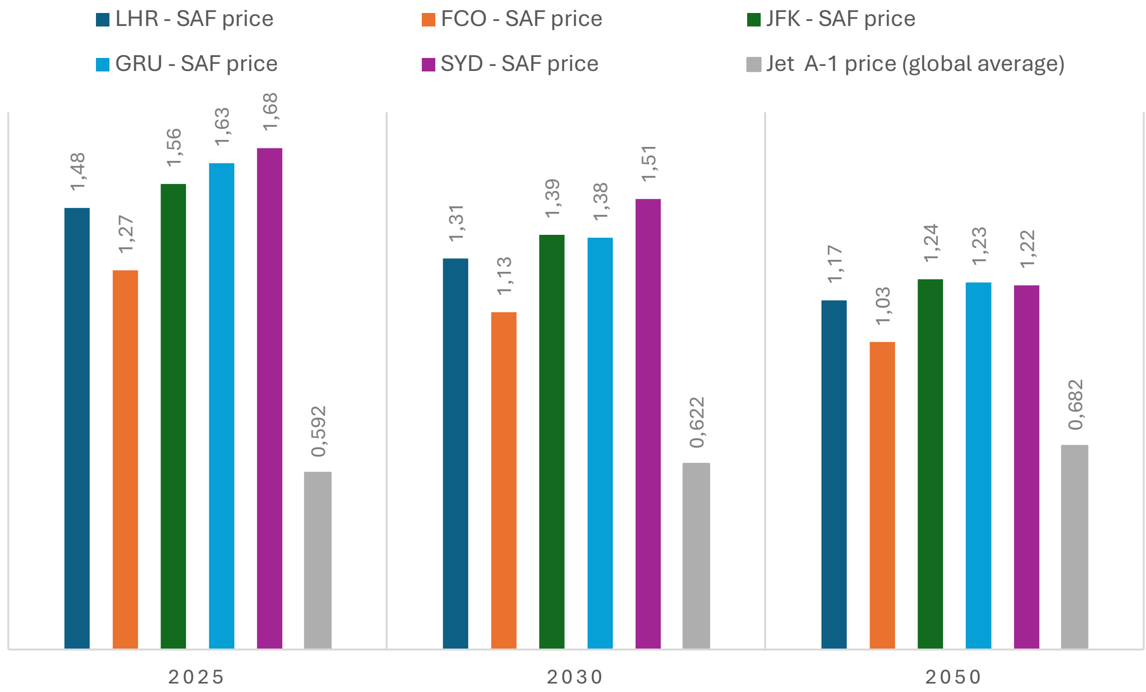


Figure 28 - Variation in Aviation Fuel Prices [€/litre]

At this point it is useful to recollect that in section 4.1 several medium range routes were considered and, for each one, the associated CO_2 emissions per passenger were calculated through the ICAO Carbon Emissions Calculator. The next step to be carried out is hence to develop an analogue process for SAF blends so to quantify emissions and fuel cost for all the same selected flight routes identified in section 4.1.

For this pourpose, a Matlab code was developed to combine data from Tables 4, 6, and 15 - 19. The analysis assumes, for all selected countries indiscriminatley, full compliance with the European ReFuelEU Aviation regulation, which mandates a progressive increase in SAF blending-from a minimum of 2% by 2025, to 6% by 2030, and ultimately 70% by 2050 across all (but only) EU airports. This phased approach aims to gradually scale up SAF production and use, supporting the EU's ambitious climate goals while allowing the industry time to adapt.

Upon these input data and with the assumptions so far introduced, it was possible to estimate the percentage of reduction in CO_2-equivalent emissions alongside the corresponding fuel cost increase for each airport under study. The findings highlight how the choice of feedstocks and production technologies significantly influences both emissions and economic burdens, reinforcing the need for innovation, targeted investment, and policy support to accelerate the deployment of the most promising SAF production pathways.

The results are presented in Tables 7 to 14, offering a clear and comparative overview of the environmental advantages and economic considerations associated with SAF adoption under the ReFuelEU framework. For a graphical representation of the data presented in this section, the reader shall refer to the figures provided in Appendix B.

These findings, together with the earlier discussions on emissions and market incentives, can provide a clear and practical overview to help policymakers, industry players, and investors to better understand the challenges and opportunities involved in adopting SAF.

In order to obtain more general information from single examples to widen the analysis perspective, data regarding all the routes from each airport was averaged to calculate what a generic route from an airport is like. It should then be recalled that the choice of the airports was firstly carried out so to represent different regions of the world, so that the average medium-range route from an airport will here be taken as an example for an entire country or region.

Then, to estimate data for entire regions, information about present and future traffic are needed. For the EU27 countries, along with the European Free Trade Association (EFTA) states and the United Kingdom, detailed and reliable data on air traffic growth and the share of medium-range flights are available. Consequently, London Heathrow and Rome Fiumicino airports are grouped within the EU27+EFTA region.

In contrast, for regions like the USA, Brazil, and Australia, the absence of comprehensive data on medium-range flight proportions necessitated a bottom-up approach. Flight schedules were analysed across different airports categorized by passenger volume and the findings were weighted by passenger numbers to estimate the share of medium-range operations over the total. While not exact, this method offers a practical and realistic reflection of actual flight patterns, forming a credible basis for emissions and cost projections.

To give a first general overview, Figures 29 and 30 illustrate the emission trends up to 2050, considering the case in which aircraft are powered exclusively with conventional aviation fuel versus with a SAF blend complying with the ReFuelEU regulation.

As Figure 29 shows, if Jet A-1 remains the only aviation fuel, emissions will increase across all studied regions, reflecting the assumption that emissions per flight remain constant while air traffic grows.

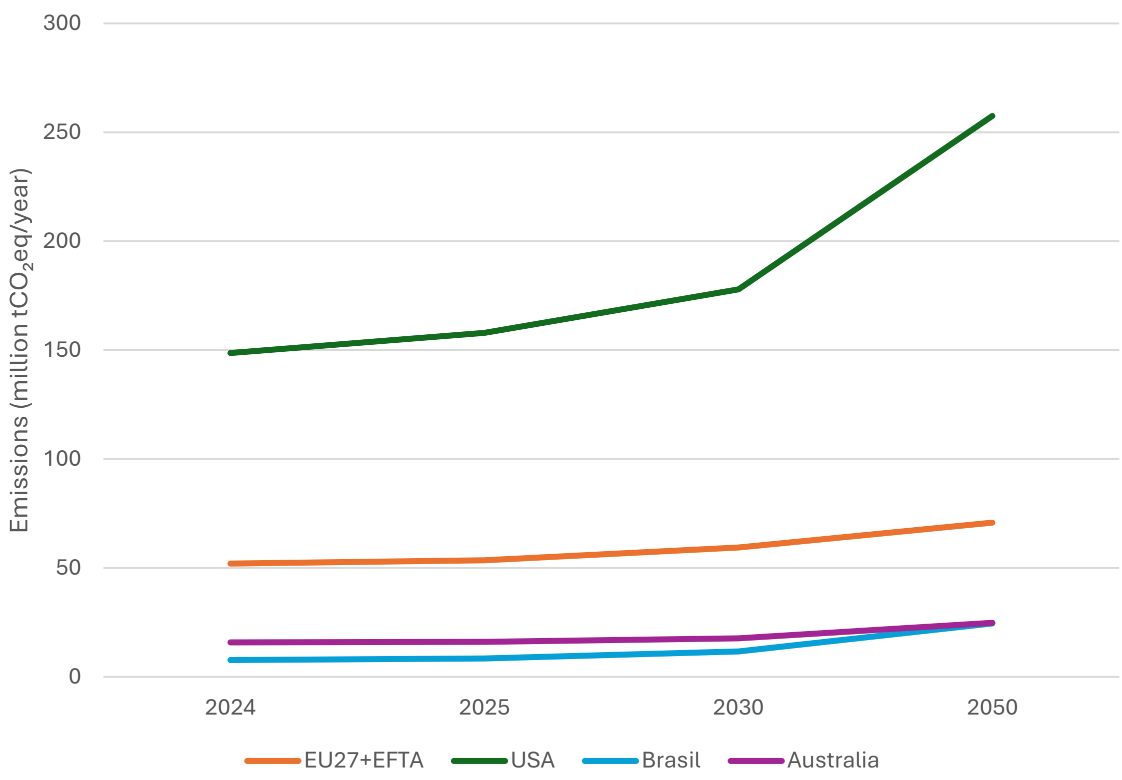


Figure 29 - Estimated annual GHG emissions - Jet A- 1

On the other hand, Figure 30 presents a markedly different trend, showing significant emission reductions by 2050 when the fuel blend contains 70% SAF. The only exception is Brazil, where emissions do not follow this downward trajectory. However, it is important to notice that even with this increase, Brazil's projected emissions with SAF remain substantially lower than if only conventional Jet A-1 fuel was used. As will be highlighted in the following sections, Brazil's SAF production relies on less efficient technologies and feedstocks, resulting in a comparatively limited overall effectiveness of the SAF strategy in this region. This outcome underscores the critical importance of feedstock selection and technological innovation in maximizing the environmental benefits of SAF.

Since this study focuses on comparisons between fuel types, potential annual emission reductions of 1–2% due to technological improvements was not considered, as it would equally impact both scenarios.

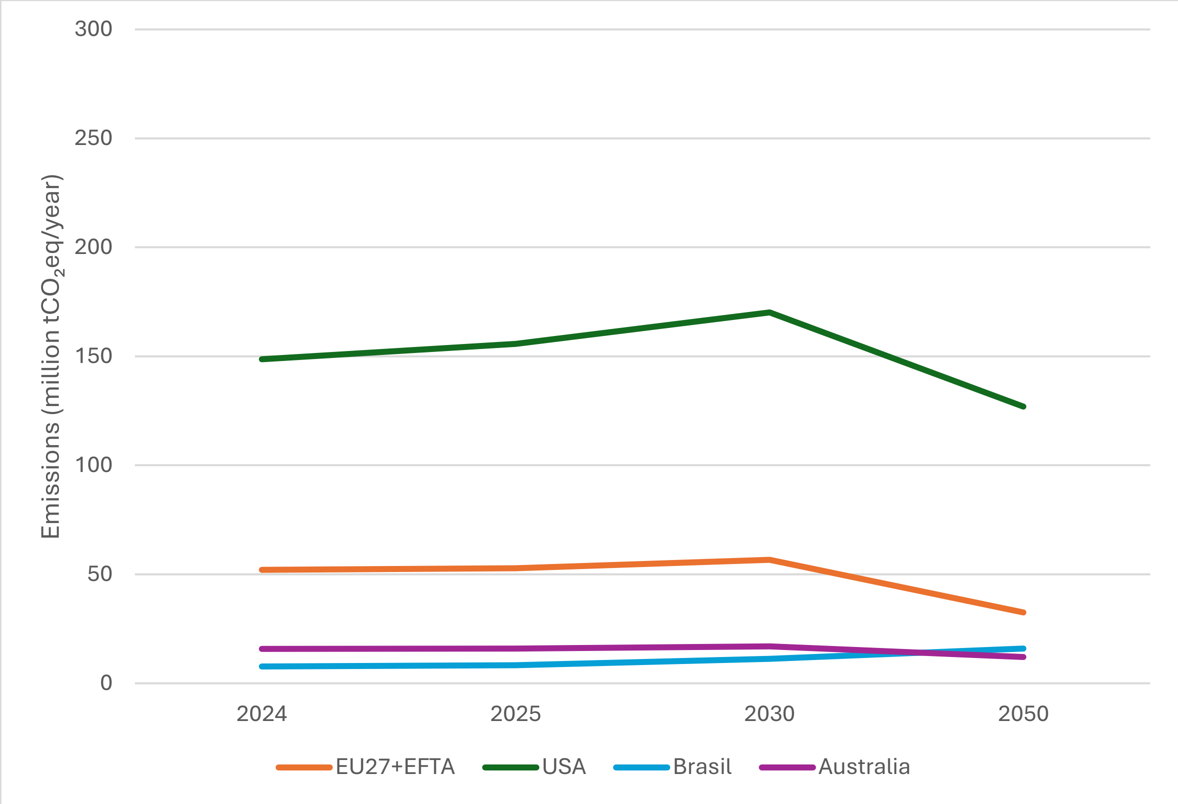


Figure 30 - Estimated annual GHG emissions - SAF blend

As illustrated in Table 7, total flights in the EU27+EFTA area are expected to increase from approximately 8.7 million in 2024 to nearly 11.8 million by 2050. Medium-range flights, which are critical for SAF deployment due to their operational profile, grow proportionally from about 2 million to 2.7 million over the same period. This steady growth reflects the region's mature but still expanding aviation market.

Table 8 illustrates the gradual impact of increasing SAF blending into conventional jet fuel, as mandated by the ReFuelEU Aviation program. While the initial effect is modest, a 1.55% reduction in greenhouse gas emissions by 2025, the benefits become far more substantial over time, reaching a 54.1% reduction by 2050. The corresponding increase in fuel costs reflects the higher proportion of SAF in the fuel mix, which currently carries a price premium over Jet A-1. However, this cost increase is moderated by the expected decrease of SAF production costs over time, while fossil jet fuel prices are likely to rise slightly. Overall, the data underscores a careful balancing act: achieving meaningful climate gains while managing the economic realities of decarbonizing aviation.

	2024	2025	2030	2050
Total flights (M/yr)	8.67	8.93	9.9	11.8
Total Medium-range flights (M/yr)	1.96	2.01	2.24	2.67

Table 7 - Total flights in EU27+EFTA [4]

		2024	2025	2030	2050
Emissions (thousand tCO_2eq/year)	SAF blend	52015	52745	56651	32507
	Jet A-1		53575	59395	70794
	Jet-A1 vs blend		-1.55%	-4.62%	-54.1%
Fuel cost (million€/year)	SAF blend	15406	16289	18629	33674
	Jet A-1		15869	18306	24086
	Jet-A1 vs blend		+2.6%	+1.8%	+39.8%

Table 8 - Estimated annual GHG emissions and fuel cost in EU27+EFTA

The United States aviation represents a significantly larger and more dynamic market. Table 9 indicates that total flights are projected to grow from 17.3 million in 2024 to nearly 30 million by 2050. Medium-range flights, the segment most relevant for SAF deployment, are also set to grow significantly, from 4.5 million to 7.8 million over the same period. As highlighted above, unlike the EU, detailed medium-range flight shares were not directly available; to address this, average estimations were obtained by analysing flight schedules from representative airports (grouped by passenger volume) and weighting the results according to the number of airports per each category: a pragmatic approach to simplify the complexity of the U.S. air travel landscape.

Table 10 shows a similar trend for emissions reductions in the U.S., going from a 1.4% in 2025 to over a 50% reduction by 2050 as SAF blending rates increase. Fuel cost also rises due to the higher SAF content, but the increase is tempered by anticipated technological advancements and production scale up of SAF production. The slightly different cost trajectory compared to the EU reflects regional market conditions and the availability of feedstocks.

	2024	2025	2030	2050
Total flights (M/yr)	17.30	18.37	20.70	29.97
Total Medium-range flights (M/yr)	4.49	4.78	5.37	7.78

Table 9 - Total flights in USA

		2024	2025	2030	2050
Emissions (thousand $tCO_2eq/year$)	SAF blend	148687	155679	170165	126952
	Jet A-1		157890	177904	257511
	Jet-A1 vs blend		-1.4%	-4.4%	-50.7%
Fuel cost (million€/year)	SAF blend	39878	43702	51183	107880
	Jet A-1		42347	49464	78942
	Jet-A1 vs blend		+3.2%	+3.5%	+36.6%

Table 10 - Estimated annual GHG emissions and fuel cost in USA

Brazil's aviation market, as shown by detailed data provided in Tables 11 and 12, is smaller but rapidly growing. Total flights are expected to rise from just under 1 million in 2024 to over 3 million by 2050, with medium-range flights expected to follow a similar trend, increasing from 290,000 to 930,000 over the same period. Due to limited availability of detailed regional data, a 2% annual growth rate was applied to estimate the evolution of medium-range operations.

The expected emissions reductions in Brazil by 2050 is approximately the 35%, a more moderate outcome compared to other regions. This is largely influenced by the types of feedstocks and production technologies commonly used in the country, where SAF production primarily relies on alcohol-to-jet (ATJ) fuels derived from sugarcane ethanol and wood chips. On the cost side, fuel prices are projected to rise by 31.5% by 2050: somewhat less than in other regions, consistently with Brazil's potential access to lower-cost bio-based feedstocks such as agricultural residues.

	2024	2025	2030	2050
Total flights (M/yr)	0.99	1.07	1.48	3.09
Total Medium-range flights (M/yr)	0.29	0.32	0.44	0.93

Table 11 - Total Flights in Brasil

		2024	2025	2030	2050
Emissions (thousand tCO_2eq/year)	SAF blend	7714	8278	11248	15943
	Jet A-1		8462	11597	24537
	Jet-A1 vs blend		-1.0%	-3.0%	-35.0%
Fuel cost (million€/year)	SAF blend	2280	2555	3666	11048
	Jet A-1		2472	3609	8400
	Jet-A1 vs blend		+3.4%	+1.6%	+31.5%

Table 12 - Estimated annual GHG emissions and fuel cost in Brasil

As shown by data in Tables 13 and 14, Australia's aviation market only shows moderate growth: total flights are expected to grow from 3 million in 2024 to about 4.7 million by 2050, with medium-range flights increasing from 650,000 to just over 1 million. Similarly to Brazil's case, a 2% annual growth rate was assumed due to limited data availability.

Australia's estimated emissions reductions and fuel cost increases are then in line with trends observed in other developed markets. Emissions are projected to decline by more than 50% by 2050, while fuel costs will rise in parallel with higher SAF blending rates and production expansion.

	2024	2025	2030	2050
Total flights (M/yr)	3.02	3.08	3.38	4.73
Total Medium-range flights (M/yr)	0.65	0.66	0.72	1.01

Table 13 - Total Flight in Australia

		2024	2025	2030	2050
Emissions (thousand tCO₂eq/year)	SAF blend	15826	15905	16943	12058
	Jet A-1		16143	17726	24816
	Jet-A1 vs blend		-1.5%	-4.4%	-51.4%
Fuel cost (million€/year)	SAF blend	5040	5342	6158	12658
	Jet A-1		5141	5963	9127
	Jet-A1 vs blend		+3.9%	+3.3%	+38.7%

Table 14 - Estimated annual GHG emissions and fuel cost in Australia

The variations observed across these regions are primarily driven by the availability of feedstocks and the production technologies in use for Sustainable Aviation Fuels. These factors have a direct impact on both the lifecycle emissions and the cost structure of sustainable fuels. This regional breakdown highlights the diversity of aviation markets worldwide and the differing trajectories of growth, emissions, and costs associated with SAF adoption. The data presented provide valuable insights that can potentially guide targeted investments toward the most efficient and cost-effective SAF pathways. Prioritizing such investments, while considering local market conditions, data availability, and policy frameworks, is essential to effectively promote SAF deployment and accelerate the decarbonization of aviation globally, all while ensuring economic sustainability.

Conclusions

This study offered a thorough and data-driven evaluation of Sustainable Aviation Fuels as a key element in the aviation sector's efforts to reduce greenhouse gas emissions and achieve long-term decarbonization. Focusing on medium-range commercial routes at five major international airports across Europe, the United States, Brazil, and Australia, the analysis highlighted how SAF deployment is shaped by a complex mix of factors, including regional feedstock availability, production technologies, regulatory frameworks, and market maturity.

The findings clearly show that SAF can enable substantial emissions reductions, with potential decreases exceeding 50% by 2050 in mature markets such as the EU and the US. These outcomes depend heavily on the choice of feedstocks and production pathways, which influence both the lifecycle carbon footprint and the economic feasibility of the fuels. While SAFs currently carry a significant price premium compared to conventional Jet A-1 fuel, often two to seven times higher, projections indicate that this gap will narrow over time thanks to technological improvements, production upscaling, and supportive policies such as the EU's ReFuelEU Aviation mandate and carbon pricing schemes. These mechanisms are crucial to incentivize low-carbon fuels and accelerate their adoption.

Regional differences remain pronounced and must be carefully considered in policy and investment decisions. Emerging markets like Brazil show promising growth in medium-range aviation and SAF use but face challenges including limited feedstock supply chains and infrastructure. For instance, Brazil's reliance on alcohol-to-jet fuels derived from sugarcane ethanol and wood chips affects both the scope of emissions reductions and cost dynamics, underscoring the importance of tailored, region-specific strategies that leverage local resources and capabilities.

In addition to reducing greenhouse gas emissions, SAF also offer benefits in terms of local air quality. Studies indicate that SAF combustion produces lower emissions of particulate matter, sulphur oxides, and other pollutants compared to conventional jet fuel. This nonetheless contributes positively to reducing health risks for communities near airports and support broader environmental goals.

The integration of life cycle assessment, detailed air traffic forecasts, emissions modeling, and cost analysis, underscores the vital role of regulatory frameworks in shaping SAF markets and the need to prioritize investments in the most promising production pathways and feedstocks. A coordinated, regionally nuanced strategy that balances environmental ambition with economic feasibility is essential to accelerate SAF adoption and drive meaningful decarbonization of global aviation.

It is important to recognize that SAF alone will not permit to fully achieve the sector's ambitious climate and decarbonisation goals: these will require a comprehensive approach that combines SAF deployment with advances in aircraft design, operational efficiencies, and emerging propulsion technologies such as electric and hydrogen-powered aircraft. Nevertheless, SAF represent a near-term, scalable solution compatible with existing infrastructure, enabling immediate emissions reductions while the industry transitions to longer-term innovations.

Appendix A

	Distance (km)	Fuel Burn (kg)	Emissions (kgCO2e)
Amman (AMM)	3679	17900	31555
Athens (ATH)	2424	8402	24588
Beirut (BEY)	3478	13475	31683
Beirut (BEY)	3478	13475	31683
Belgrade (BEG)	1698	7128	27253
Bucharest (OTP)	2102	8921	27522
Cairo (CAI)	3529	16710	34601
Casablanca (CMN)	2092	8399	22228
Gibraltar (GIB)	1745	7749	23912
Helsinki (HEL)	1846	10788	22853
Istanbul (IST)	2485	15578	28433
Larnaca (LCA)	3275	10328	30920
Ljubljana (LJU)	1233	5964	19108
Luxor (LXR)	4001	12347	39502
Malta (MLA)	2100	8914	27416
Marrakech (RAK)	2293	8680	25124
Reykjavik (KEF)	1894	8072	20973
Sofia (SOF)	2039	7627	25810
Tel Aviv (TLV)	3586	19344	27471
Tirana (TIA)	1896	7604	23286

Table 15 - Outbound flight paths from London Heathrow (LHR)

	Distance (km)	Fuel Burn (kg)	Emissions (kgCO2e)
Amman (AMM)	2382	7946	24077
Cairo (CAI)	2150	8428	22806
Casablanca (CMN)	1973	8204	25869
Doha (DOH)	4036	30037	35051
Dublin (DUB)	1883	7991	24050
Fuerteventura (FUE)	2779	10599	31045

Funchal (FNC)	2741	9682	22425
Giza (SPX)	2115	7788	17207
Gran Canaria (LPA)	2932	11044	32347
Helsinki (HEL)	2232	9681	30029
Jeddah (JED)	3362	12046	30140
Kuwait (KWI)	3489	13429	31762
Lisbon (LIS)	1836	7336	20727
Marsa Alam (RMF)	2729	10013	25124
Paphos (PFO)	1928	7576	21982
Riyadh (RUH)	3669	12918	35820
Sharm El Sheikh (SSH)	2525	9468	23823
Stockholm (ARN)	2021	7279	21588
Tel Aviv (TLV)	2277	8996	21074
Tenerife (TFS)	3016	10521	26646
Yerevan (EVN)	2688	9521	22054

Table 16 - Outbound flight paths from Rome Fiumicino (FCO)

	Distance (km)	***Fuel Burn (kg)***	***Emissions (kgCO2e)***
Aguadilla (BQN)	2541	11006	32931
Austin (AUS)	2445	9698	30830
Bogota (BOG)	3993	17101	30286
Cancun (CUN)	2504	9821	28848
Denver (DEN)	2609	9409	30284
Kingston (KIN)	2538	10138	32625
Las Vegas (LAS)	3608	12971	35682
Medellin (MDE)	3835	13213	31105
Mexico City (MEX)	3364	13782	34894
Montego Bay (BBJ)	2491	10287	29289
Phoenix (PHX)	3455	11556	32856
Punta Cana (PUJ)	2506	10359	29635
Salt Lake City (SLC)	3191	11743	31709
San Diego (SAN)	3925	13930	38637

San Jose (SJO)	3557	13587	44668
San Juan (SJU)	2575	10370	29403
San Salvador (SAL)	3368	11689	34045
Santiago (STI)	2379	9899	29076
Santo Domingo (SDQ)	2499	9907	29485
Seattle (SEA)	3885	13765	37899
Tobago (TAB)	3515	10732	31575
Vancouver (YVR)	3928	14636	42327

Table 17 - Outbound flight paths from New York (JFK)

	Distance (km)	**Fuel Burn (kg)**	**Emissions (kgCO2e)**
Belem (BEL)	2459	10470	27739
Fortaleza (FOR)	2345	10468	25693
Joao Pessoa (JPA)	2372	9545	26582
Juazeiro Do Norte (JDO)	1957	8392	23190
Lima (LIM)	3471	14871	33385
Macapa (MCP)	2654	10686	30209
Maceio (MCZ)	2327	10263	25790
Manaus (MAO)	2694	11401	28158
Natal (NAT)	2293	9819	25701
Porto Velho (PVH)	2472	10069	28844
Recife (REC)	2099	8876	21778
Santiago (SCL)	2614	12246	27238
Sao Luiz (SLZ)	1918	8649	22708
Teresina (THE)	2078	8728	24905

Table 18- Outbound flight paths from Sao Paulo (GRU)

	Distance (km)	**Fuel burn (kg)**	**Emissions (kgCO2e)**
Alice Springs (ASP)	2018	8334	21906
Auckland (AKL)	2158	10884	21472
Cairns (CNS)	1971	8531	20925

Christchurch (CHC)	2124	15323	22316
Darwin (DRW)	3153	11849	31104
Nadi (NAN)	3167	13882	27837
Perth (PER)	3275	13923	31462
Queenstown (ZQN)	1938	7863	20923
Wellington (WLG)	2227	8436	22830

Table 19 - Outbound flight paths from Sydney (SYD)

	2024 emissions (KgCO2e)	**2025 emissions (2% SAF) (KgCO2e)**	**2030 emissions (6% SAF) (KgCO2e)**	**2050 emissions (70% SAF) (KgCO2e)**
Amman (AMM)	31555.00	31075.19	30115.56	14761.54
Athens (ATH)	24588.00	24214.12	23466.37	11502.35
Beirut (BEY)	31683.00	31201.24	30237.72	14821.41
Belgrade (BEG)	27253.00	26838.60	26009.80	12749.05
Bucharest (OTP)	27522.00	27103.51	26266.53	12874.88
Cairo (CAI)	34601.00	34074.87	33022.61	16186.46
Casablanca (CMN)	22228.00	21890.01	21214.03	10398.33
Gibraltar (GIB)	23912.00	23548.40	22821.21	11186.11
Helsinki (HEL)	22853.00	22505.51	21810.52	10690.71
Istanbul (IST)	28433.00	28000.66	27135.98	13301.05
Larnaca (LCA)	30920.00	30449.84	29509.53	14464.48
Ljubljana (LJU)	19108.00	18817.45	18236.35	8938.79
Luxor (LXR)	39502.00	38901.35	37700.04	18479.17
Malta (MLA)	27416.00	26999.12	26165.37	12825.30
Marrakech (RAK)	25124.00	24741.97	23977.92	11753.09
Reykjavik (KEF)	20973.00	20654.09	20016.28	9811.24
Sofia (SOF)	25810.00	25417.54	24632.63	12074.01
Tel Aviv (TLV)	27471.00	27053.29	26217.86	12851.03
Tirana (TIA)	23286.00	22931.92	22223.77	10893.27
		-1.52 %	-4.56 %	-53.22 %

Table 20 - Medium range routes from London Heathrow (LHR): emissions

	2024 fuel cost (JET A-1) (€)	2025 fuel cost (2% SAF) (€)	2030 fuel cost (6% SAF) (€)	2050 fuel cost (70% SAF) (€)
Amman (AMM)	13246.00	13643.38	14714.69	22889.62
Athens (ATH)	6217.48	6404.00	6906.86	10744.06
Beirut (BEY)	9971.50	10270.65	11077.12	17231.16
Belgrade (BEG)	5274.72	5432.96	5859.57	9114.93
Bucharest (OTP)	6601.55	6299.59	7333.51	11407.73
Cairo (CAI)	12365.40	12736.36	13736.46	21367.91
Casablanca (CMN)	6215.26	6401.72	3904.40	10740.22
Gibraltar (GIB)	5734.26	5906.29	6370.07	9909.03
Helsinki (HEL)	7983.12	8222.61	8868.28	13795.15
Istanbul (IST)	11527.72	11873.55	12805.89	19920.37
Larnaca (LCA)	7642.72	7872.00	8490.13	13206.93
Ljubljana (LJU)	4413.36	4545.76	4902.71	7626.47
Luxor (LXR)	9136.78	9410.88	10149.85	15788.73
Malta (MLA)	6596.36	6794.25	7327.75	11398.78
Marrakech (RAK)	6423.20	6615.90	7135.39	11099.55
Reykjavik (KEF)	5973.28	6152.48	6635.59	10322.07
Sofia (SOF)	5643.98	5813.30	6269.78	9753.03
Tel Aviv (TLV)	14314.56	14744.00	15901.74	24736.14
Tirana (TIA)	5626.96	5795.77	6250.87	9723.61
		3.02 %	6.76 %	50.44 %

Table 21 - Medium range routes from London Heathrow (LHR): cost

	2024 emissions (KgCO2e)	2025 emissions (2% SAF) (KgCO2e)	2030 emissions (6% SAF) (KgCO2e)	2050 emissions (70% SAF) (KgCO2e)
Amman (AMM)	24077.00	23701.04	22949.11	10918.27
Cairo (CAI)	22806.00	22449.88	21737.65	10341.91
Casablanca (CMN)	25869.00	25465.05	24657.16	11730.89

Doha (DOH)	35051.00	34503.68	33409.03	15894.68
Dublin (DUB)	24050.00	23674.46	22923.37	10906.03
Fuerteventura (FUE)	31045.00	30560.23	29590.69	14078.07
Funchal (FNC)	22425.00	22074.83	21374.50	10169.13
Giza (SPX)	17207.00	16938.31	16400.94	7802.91
Gran Canaria (LPA)	32347.00	31841.90	30831.70	14668.49
Helsinki (HEL)	30029.00	29560.10	28622.29	13617.34
Jeddah (JED)	30140.00	29669.36	28728.09	13667.68
Kuwait (KWI)	35820.00	35260.67	34142.01	16243.40
Lisbon (LIS)	20727.00	20403.35	19756.04	9399.14
Marsa Alam (RMF)	25124.00	24731.69	23947.06	11393.06
Paphos (PFO)	21982.00	21638.75	20952.25	9968.24
Riyadh (RUH)	31762.00	31266.03	30274.10	14403.21
Sharm El Sheikh (SSH)	23823.00	23451.00	22707.01	10803.09
Stockholm (ARN)	21588.00	21250.90	20576.71	9789.58
Tel Aviv (TLV)	21074.00	20744.93	20086.78	9556.49
Tenerife (TFS)	26646.00	26229.92	25397.76	12083.24
Yerevan (EVN)	22054.00	21709.63	21020.88	10000.89
		-1.56 %	-4.68 %	-54.65 %

Table 22 - Medium range routes from Rome Fiumicino (FCO): emissions

	2024 fuel cost (JET A-1) (€)	***2025 fuel cost (2% SAF) (€)***	***2030 fuel cost (6% SAF) (€)***	***2050 fuel cost (70% SAF) (€)***
Amman (AMM)	5880.04	6014.72	6424.74	9187.56
Cairo (CAI)	6236.72	6379.57	6814.46	9744.88
Casablanca (CMN)	6070.96	6210.02	6633.34	9485.87
Doha (DOH)	22227.38	22736.51	24286.42	34730.28
Dublin (DUB)	5913.34	6048.79	6461.12	9239.59
Fuerteventura (FUE)	7843.26	8022.91	8569.82	12255.09

Funchal (FNC)	7164.68	7328.79	7828.38	11194.81
Giza (SPX)	5763.12	5895.13	6296.99	9004.88
Gran Canaria (LPA)	8172.56	8359.76	8929.63	12769.62
Helsinki (HEL)	7163.94	7328.03	7827.57	11193.66
Jeddah (JED)	8914.04	9118.22	9739.79	13928.19
Kuwait (KWI)	9937.46	10165.08	10858.02	15527.28
Lisbon (LIS)	5428.64	5552.99	5931.52	8482.25
Marsa Alam (RMF)	7409.62	7579.34	8096.01	11577.53
Paphos (PFO)	5606.24	5734.65	6125.57	8759.75
Riyadh (RUH)	9559.32	9778.28	10444.85	14936.44
Sharm El Sheikh (SSH)	7006.32	7166.80	7655.35	10947.37
Stockholm (ARN)	5386.46	5509.84	5885.44	8416.34
Tel Aviv (TLV)	6657.04	6809.52	7273.72	10401.62
Tenerife (TFS)	7785.54	7963.87	8506.75	12164.91
Yerevan (EVN)	7045.54	7206.92	7698.20	11008.66
		2.30 %	5.01 %	36.03 %

Table 23 - Medium range routes from Rome Fiumicino (FCO): cost

	2024 emissions (KgCO2e)	***2025 emissions (2% SAF) (KgCO2e)***	***2030 emissions (6% SAF) (KgCO2e)***	***2050 emissions (70% SAF) (KgCO2e)***
Aguadilla (BQN)	32931.00	32453.97	3499.90	16234.83
Austin (AUS)	30830.00	30383.40	29490.20	15199.05
Bogota (BOG)	30286.00	29847.28	28969.85	14930.86
Cancun (CUN)	28848.00	28430.11	8217.23	14221.93
Denver (DEN)	30284.00	29845.31	28967.93	14929.88
Kingston (KIN)	32625.00	32152.40	31207.20	16083.98
Las Vegas (LAS)	35682.00	35165.12	34131.35	17591.07
Medellin (MDE)	31105.00	30654.42	29753.25	15334.63
Mexico City (MEX)	34894.00	34388.53	33377.59	17202.59

Montego Bay (BBJ)	29289.00	28864.72	28016.17	14439.35
Phoenix (PHX)	32856.00	32380.05	31428.16	16197.86
Punta Cana (PUJ)	29635.00	29205.71	28347.14	14609.92
Salt Lake City (SLC)	31709.00	31249.67	30331.01	15632.39
San Diego (SAN)	38637.00	38077.31	36957.93	19047.87
San Jose (SJO)	44668.00	44020.95	42726.84	22021.12
San Juan (SJU)	29403.00	28977.07	28125.22	14495.55
San Salvador (SAL)	34045.00	33551.83	31565.49	16784.03
Santiago (STI)	29076.00	28654.81	27812.43	14334.34
Santo Domingo (SDQ)	29485.00	29057.88	28203.65	14535.97
Seattle (SEA)	37899.00	37350.00	36252.00	18684.04
Tobago (TAB)	31575.00	31117.61	30202.83	15566.33
Vancouver (YVR)	42327.00	41713.86	40487.57	20867.02
		-1.45 %	-4.35 %	-50.70 %

Table 24 - Medium range routes from New York (JFK): emissions

	2024 fuel cost (JET A-1) (€)	***2025 fuel cost (2% SAF) (€)***	***2030 fuel cost (6% SAF) (€)***	***2050 fuel cost (70% SAF) (€)***
Aguadilla (BQN)	8254.50	8518.64	9208.72	14781.06
Austin (AUS)	7273.50	7506.25	8114.32	13024.41
Bogota (BOG)	12825.75	13236.17	14308.41	22966.64
Cancun (CUN)	7365.75	7601.45	8217.23	13189.60
Denver (DEN)	7056.75	7282.57	7872.51	12636.29
Kingston (KIN)	7603.50	7846.81	8482.46	13615.33
Las Vegas (LAS)	9728.25	10039.55	10852.84	17420.05
Medellin (MDE)	9909.75	10226.86	11055.32	17745.06
Mexico City (MEX)	10336.50	10667.27	11531.40	18509.23
Montego Bay (BBJ)	7715.25	7962.14	8607.13	13815.44
Phoenix (PHX)	8667.00	8944.34	9668.91	15519.71

Punta Cana (PUJ)	7769.25	8017.87	8667.38	13912.14
Salt Lake City (SLC)	8807.25	9089.08	9825.37	15770.85
San Diego (SAN)	10447.50	10781.82	11655.23	18707.99
San Jose (SJO)	10190.25	10516.34	11368.24	18247.34
San Juan (SJU)	7777.50	8026.38	8676.58	13926.91
San Salvador (SAL)	8766.75	9047.29	9780.19	15698.33
Santiago (STI)	7424.25	7661.83	8282.49	13294.36
Santo Domingo (SDQ)	7430.25	7668.02	8289.19	13305.10
Seattle (SEA)	10323.75	10654.11	11517.18	18486.39
Tobago (TAB)	8049.00	8306.57	8979.46	14413.08
Vancouver (YVR)	10977.00	11328.26	12245.94	19656.15
		3.20 %	7.27 %	56.16 %

Table 25 - Medium range routes from New York (JFK): cost

	2024 emissions (KgCO2e)	**2025 emissions (2% SAF) (KgCO2e)**	**2030 emissions (6% SAF) (KgCO2e)**	**2050 emissions (70% SAF) (KgCO2e)**
Belem (BEL)	27739.00	27461.49	26906.46	18025.99
Cruz (JJD)	26582.00	26316.06	25784.18	17274.12
Fortaleza (FOR)	25693.00	25435.95	24921.86	16696.41
Joao Pessoa (JPA)	24514.00	24268.75	23778.25	15930.24
Juazeiro Do Norte (JDO)	23190.00	22958.00	22493.99	15069.85
Lima (LIM)	33385.00	33051.00	32383.00	21695.00
Macapa (MCP)	30209.00	29906.77	29302.32	19631.10
Maceio (MCZ)	22708.00	22480.82	22026.45	14756.63
Manaus (MAO)	28158.00	27876.29	27312.88	18298.27
Natal (NAT)	25701.00	25443.87	24929.62	16701.61
Porto Velho (PVH)	28844.00	28555.43	27978.29	18744.06

Recife (REC)	21778.00	21560.12	21124.37	14152.27
Santiago (SCL)	27238.00	26965.50	26420.49	17700.42
Sao Luiz (SLZ)	25790.00	25531.98	25015.95	16759.44
Teresina (THE)	24905.00	24655.84	24157.51	16184.33
		-1.00 %	-3.00 %	-35.02 %

Table 26 - Medium range routes from Sao Paulo (GRU): emissions

	2024 fuel cost (JET A-1) (€)	***2025 fuel cost (2% SAF) (€)***	***2030 fuel cost (6% SAF) (€)***	***2050 fuel cost (70% SAF) (€)***
Belem (BEL)	7957.20	8224.71	8957.08	14032.42
Cruz (JJD)	7254.20	7498.07	8165.75	12792.69
Fortaleza (FOR)	7955.68	8223.14	8955.37	14029.74
Joao Pessoa (JPA)	7397.84	7646.54	8327.44	13045.99
Juazeiro Do Norte (JDO)	6377.92	6592.34	7179.36	11247.38
Lima (LIM)	11301.96	11681.91	12722.14	19930.86
Macapa (MCP)	8121.36	8394.39	9141.87	14321.91
Maceio (MCZ)	6573.24	6794.22	7399.22	11591.82
Manaus (MAO)	8664.76	8956.06	9753.56	15280.19
Natal (NAT)	7462.44	7713.32	8400.15	13159.91
Porto Velho (PVH)	7652.44	7909.70	8614.03	13494.98
Recife (REC)	6745.76	6972.54	7593.42	11896.06
Santiago (SCL)	9306.96	9619.85	10476.45	16412.70
Sao Luiz (SLZ)	7799.88	8062.10	8780.00	13754.99
Teresina (THE)	6633.28	6856.28	7466.80	11697.70
		3.36 %	6.94 %	52.30 %

Table 27 - Medium range routes from Sao Paulo (GRU): cost

	2024 emissions (KgCO2e)	2025 emissions (2% SAF) (KgCO2e)	2030 emissions (6% SAF) (KgCO2e)	2050 emissions (70% SAF) (KgCO2e)
Alice Springs (ASP)	21906.00	21584.24	20940.71	10644.32
Auckland (AKL)	21472.00	21156.61	20525.84	10433.44
Cairns (CNS)	20925.00	20617.65	20002.94	10167.65
Christchurch (CHC)	22316.00	21988.22	21322.65	10843.54
Darwin (DRW)	31104.00	30647.13	29733.40	15113.71
Nadi (NAN)	27837.00	27428.12	26610.36	13526.25
Perth (PER)	31462.00	30999.88	30075.63	15287.67
Queenstown (ZQN)	20923.00	20615.68	20001.03	10166.67
Wellington (WLG)	22830.00	22494.67	21824.00	11093.30
		-1.47 %	-4.41 %	-51.41 %

Table 28 - Medium range routes from Sydney (SYD): emissions

	2024 fuel cost (JET A-1) (€)	2025 fuel cost (2% SAF) (€)	2030 fuel cost (6% SAF) (€)	2050 fuel cost (70% SAF) (€)
Alice Springs (ASP)	5917.14	6148.83	6819.30	10946.71
Auckland (AKL)	7727.64	8030.22	8905.83	14296.13
Cairns (CNS)	6057.01	6294.17	6980.49	11205.47
Christchurch (CHC)	10879.33	11305.31	12538.04	20126.76
Darwin (DRW)	8412.79	8742.19	9695.44	15563.66
Nadi (NAN)	9856.22	10242.14	11358.95	18234.01
Perth (PER)	9885.33	10272.39	11392.49	18287.86
Queenstown (ZQN)	5582.73	5801.32	6433.90	10328.05
Wellington (WLG)	5989.56	6224.08	6902.76	11080.69
		3.92 %	9.10 %	60.18 %

Table 29 - Medium range routes from Sydney (SYD): cost

Appendix B

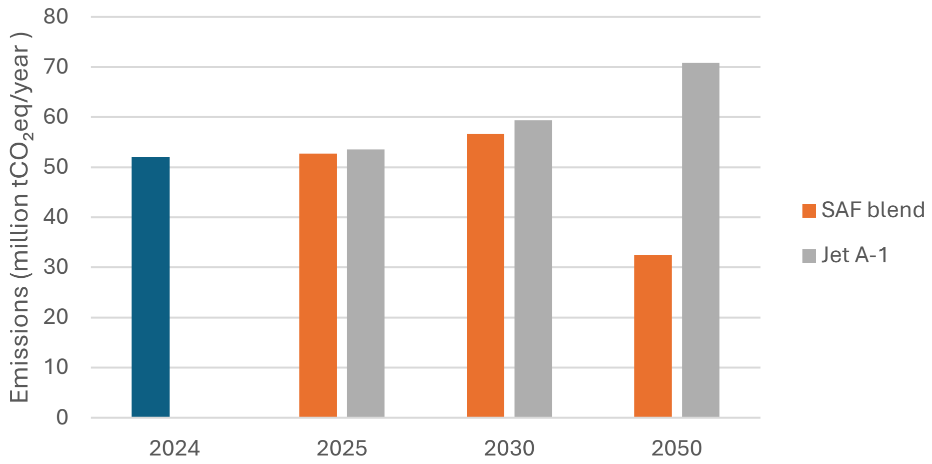


Figure 31 - Estimated annual GHG emissions in EU27+EFTA

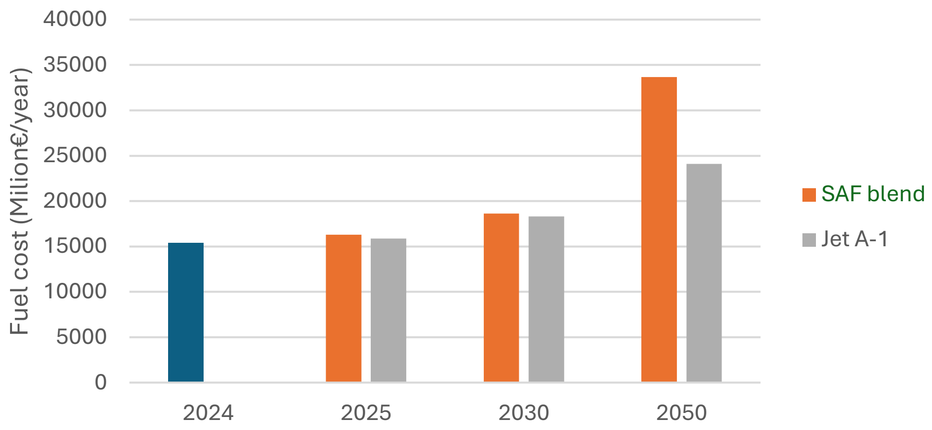


Figure 32 - Estimated annual fuel cost in EU27+EFTA

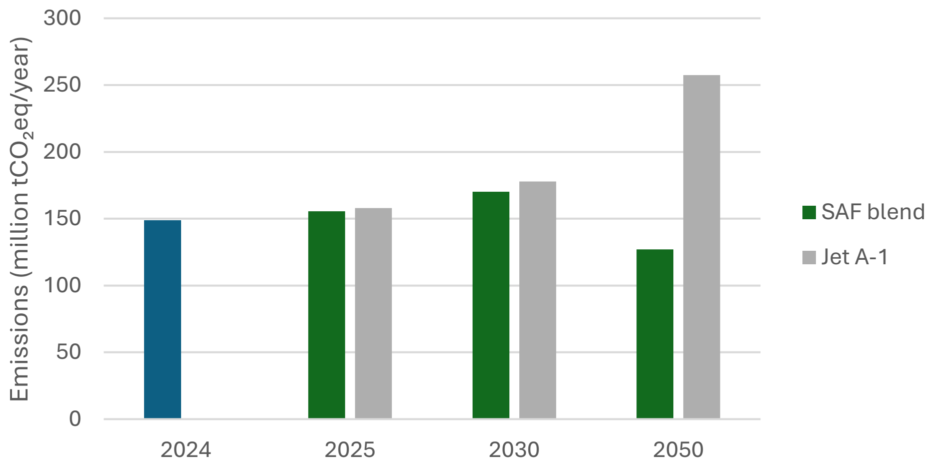


Figure 33 - Estimated annual GHG emissions in USA

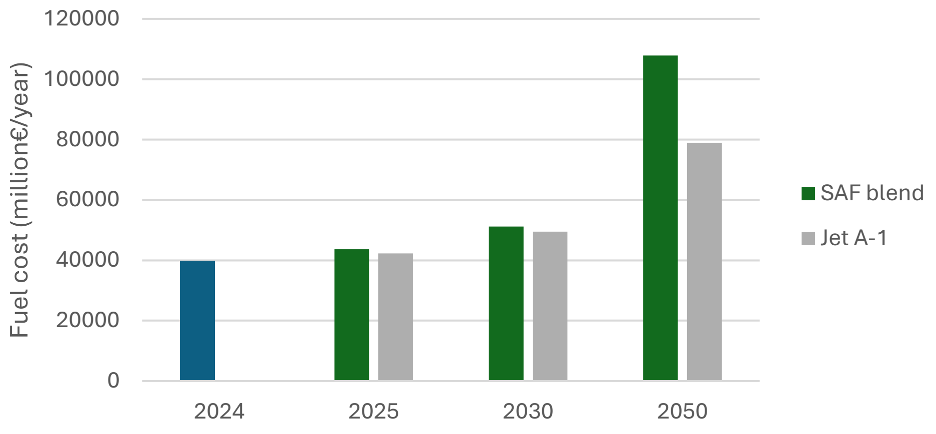


Figure 34 - Estimated annual fuel cost in USA

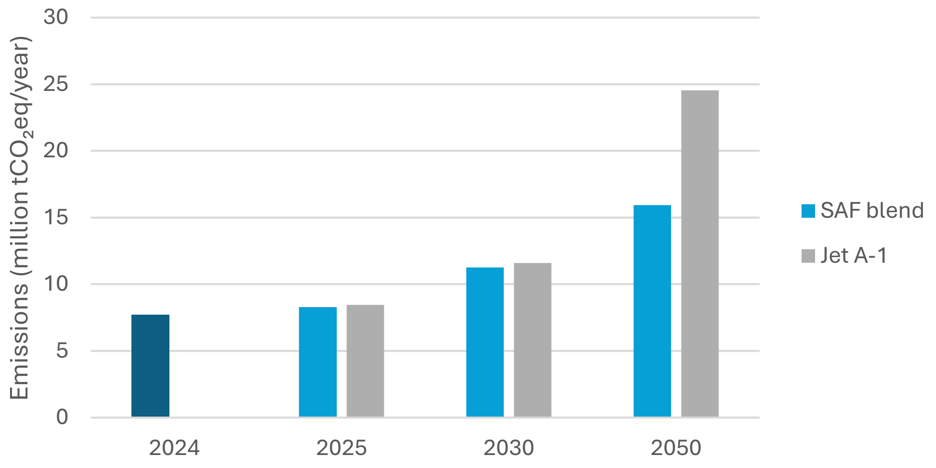


Figure 35 - Estimated annual GHG emissions in Brasil

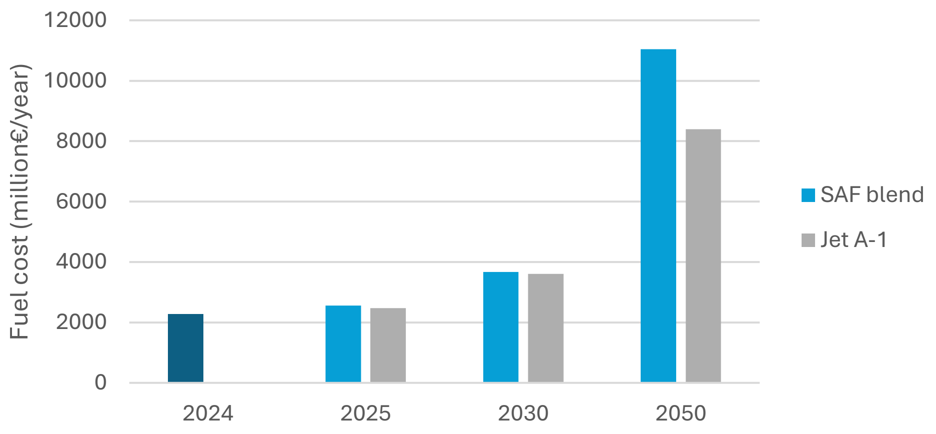


Figure 36 - Estimated annual fuel cost in Brasil

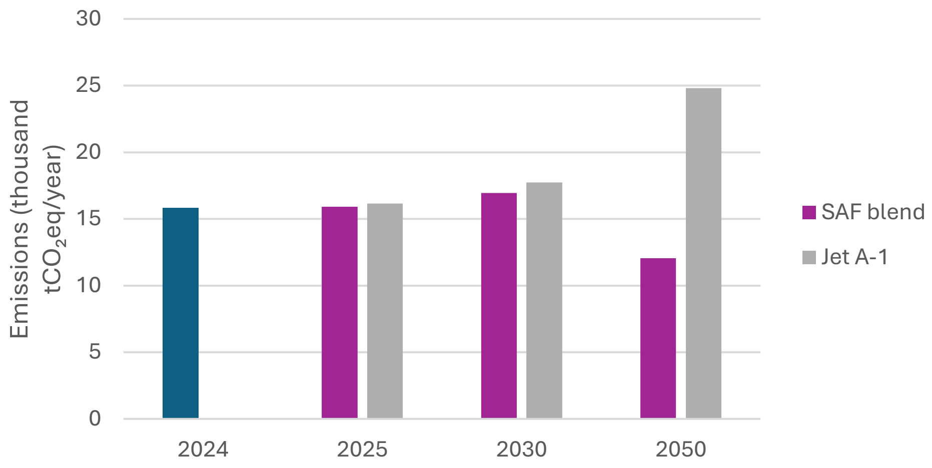


Figure 37 - Estimated annual GHG emissions in Australia

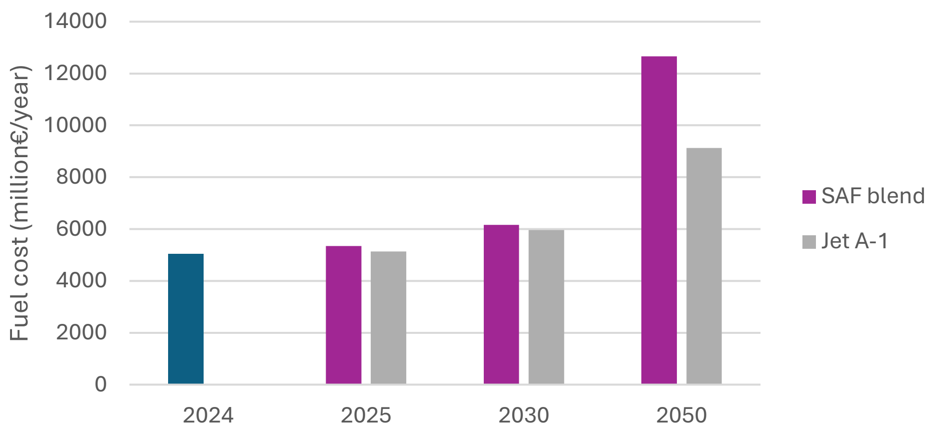


Figure 38 - Estimated annual fuel cost in Australia

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