Will Sustainable Aviation Fuel (SAF) be able to meet future demand for sustainable air travel, and if so, at what cost?

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Will Sustainable Aviation Fuel (SAF) be able to meet future demand for sustainable air travel, and if so, at what cost?

Master of Science in Commodity Trading

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I certify that the work presented here is, to the best of my knowledge and belief, original and the result of my own investigations, except as acknowledged, and has not been submitted, either in part or whole, for a degree at this or any other University.

Signature:

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Executive Summary

Sustainable Aviation Fuel (SAF) can partially meet future demand for sustainable air travel, but this will come at both an environmental and considerable financial cost. While SAF is critical to the aviation industry's decarbonization efforts, its ability to scale is constrained by feedstock availability, high production costs, and increasing political and societal resistance to climate actions.

Currently, SAF production accounts for only 0.3% of global jet fuel supply and needs to considerably scale up in order to meet the 445m MT required annually by 2050 to meet climate targets. The industry is heavily reliant on HEFA-based pathways, which depend on limited feedstocks like used cooking oil and animal fats, while alternative methods face technological immaturity and high costs. Production costs are also significantly higher than fossil-based jet fuel, and airlines are likely to pass these expenses onto passengers and cargo customers, potentially raising ticket prices by up to 16% by 2038, especially for long-haul flights. However, the costs are not only monetary as transitioning to SAF also involves environmental trade-offs, such as the challenges of sustainable feedstock sourcing and lifecycle emissions, with investments in infrastructure and technology.

Political resistance and climate skepticism further complicate SAF adoption. In the United States, key SAF tax credits under the Inflation Reduction Act are set to expire by 2027, with uncertain renewal in the face of increasing opposition to climate policies. Similarly, right-wing movements in Europe have opposed green mandates, citing economic strain and public dissatisfaction with sustainability initiatives. These sentiments reflect broader challenges as public attention shifts to inflation, energy security, and the perceived costs of climate action. The aviation sector also faces competition for renewable feedstocks from industries like shipping and road transport, further intensifying the need for resource prioritization.

Despite these barriers, regulatory frameworks such as the EU's ReFuelEU Aviation Regulation, which mandates blending targets of 2% SAF by 2025 and 70% by 2050, Carbon Credits and financial incentives like current SAF subsidies in the United States, are fostering adoption. Additionally, technological advancements and economies of scale are expected to reduce production costs over time, though this requires sustained investment and political commitment.

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Glossary

k:	Thousand
m:	Million
bn:	Billion
kg:	Kilogram
MT:	Metric Tonnes
H_2:	Hydrogen
LH_2:	Liquid Hydrogen
O:	Oxygen
CO:	Carbon Monoxide
CO_2:	Carbon Dioxyde
NO_x:	Nitrogen Oxides
FOG:	Waste Fats, Oils and Greases
UCO:	Used Cooking Oil
MSW:	Municipal Solid Waste
LNG:	Liquefied Natural Gas
FFA:	Free Fatty Acids
DAC:	Direct Air Capture
GHG:	Greenhouse Gas
SAF:	Sustainable Aviation Fuel
ESG:	Environment, Social, Governance
SPK:	Synthetic Paraffinic Kerosene
SK:	Synthetic Kerosene
SKA:	Synthetic Kerosene and Aromatics
PTL:	Power-to-Liquid
NGO:	Non-Governmental Organizations
ASTM:	American Society for Testing Materials

ICAO: International Civil Aviation Organization

IEA: International Energy Agency

CORSIA: Carbon Offsetting and Reduction Scheme for International Aviation

CAPEX: Capital Expenditure

EU ETS: European Emissions Trading System

RED II: Renewable Energy Directive II

EEA: European Economic Area

DOT: Department of Transportation

DOE: Department of Energy

USDA: U.S. Department of Agriculture

EPA: Environmental Protection Agency

IRA: Inflation Reduction Act

APU: Auxiliary Power Units

PoS: Proof of Sustainability

PoC: Proof of Compliance

LCA: Lifecycle Analysis

CTK: Cargo Tonne Kilometers

PM: Particulate Matter

DLUC: Direct Land Use Change

ILUC: Indirect Land Use Change

CAGR: Compound Annual Growth Rate

YoY: Year on Year

R&D: Research & Development

RD&D: Research, Development, and Demonstration

EBITDA: Earnings Before Interest, Taxes, Depreciation, and Amortization

1. Introduction

Aviation has long been a pillar of global connectivity, enabling economic growth and fostering international collaboration. Nevertheless, as the industry continues to expand, it faces growing pressure to adapt to evolving challenges and priorities. The need for innovative solutions to ensure the sector's long-term resilience, efficiency, and sustainability has never been more pressing.

1.1 Background and Context

1.1.1 Overview of global aviation's environmental impact.

The aviation sector is significantly contributing to climate change by the two types of emissions: CO_2 and non-CO_2. As it stands today, the air transport industry accounts for around two and a half percent of the total carbon dioxide output around the globe. To put this into perspective, air travel accounts for 10% of emissions from all types of transportation (Emissions of Carbon Dioxide in the Transportation Sector | Congressional Budget Office, 2022). However, as the last decade came to a close, both global and aviation emissions increased significantly. Notably, 47% of total aviation CO_2 emissions from 1940 to 2019 occurred after 2000, driven by a rise in demand for air travel (Klöwer et al., 2021).

Whereas carbon emissions from the burning of fuel can be fairly ascribed, there are non-CO_2 emissions like nitrogen oxides (NO_x), water vapor, soot, and sulfate particles which have more complex and often less-known roles in warming the atmosphere. These emissions meet climate systems when redirection of atmospheric chemical processes happens from those emissions and when contrails are formed along with their cirrus clouds[1], which can cause a greenhouse effect. Their effects are closely linked to flight altitude and the state of the atmosphere.

However, as a response to these challenges, the industry is diversifying its mitigation strategies. A key argument regarding Sustainable Aviation Fuel (SAF) is its success in reducing lifecycle CO_2 emissions, in comparison to conventional kerosene. Moreover, advanced flight planning techniques aim to avoid the creation of contrails by flying in as few airspaces and as low altitude as possible. But these last initiatives are also presented as attempts to reduce NO_x without dramatically altering the operation of the engine. However, due to the non-linear and multi-faceted character of the non-carbon gases effects, integrating effective solutions remains complicated (EASA EAER 2022, n.d.).

[1] Cirrus clouds: high cloud made of ice crystals

Further studies together with a range of policies targeted at these impacts are necessary for controlling aviation's climate impact. There is still much debate about the concrete systems and intensity of non-CO_2 impact effects on climate and this stresses the importance of such research efforts.

1.1.1.1 Sustainable Aviation Fuel (SAF) and its role in decarbonizing aviation

SAF is a novel liquid fuel for commercial aviation that can decrease CO_2 emissions by as much as 80% in comparison to traditional kerosene. It is derived from a range of sustainable feedstocks, including but not limited to, waste oils, fats, municipal solid waste, and non-food crops, or synthetically through carbon capture from the atmosphere.

SAF is produced through the synthetic paraffinic kerosene (SPK) route, a technology that provides the basic structure for kerosene fuels. Nonetheless, SPK is deficient in important aromatics and cyclic chain alkanes, rendering it incompatible with reactivity specifications of aviation kerosene, why it must be blended with traditional aviation kerosene (Wang et al., 2024). Unlike fossil fuels, which only combust stored carbon, SAF recycles CO_2 absorbed by biomass throughout its life cycle. Although SAF is a more sustainable alternative than fossil-based fuels, it still emits some GHG during its lifecycle, however to a much lower extent than traditional aviation fuels. Thus, SAF is essential for achieving decarbonization in the aviation industry.

1.2 Objectives of the Study

The study will actively measure the many ecological benefits of SAF by identifying its lifecycle emissions while exploring how key stakeholders, such as airlines, governments and investors, promote greater SAF adoption. A thorough comprehension of SAF's potential as an economically viable solution for decarbonizing the aviation industry is sought through several important factors such as: the challenges in scalability in order to meet the expected increase in global air travel demand, the competition between other sectors, the economic and environmental effects of production, distribution and adoption of the product, the needed technical improvements, the required infrastructure, as well as relevant regulatory and policy frameworks. Lastly, the research will examine whether SAF can realistically meet the future demand for aviation fuel and at what cost.

1.3 Problem Statement

The aviation industry is one of the large contributors to the global GHG emissions, which is why it needs to de-carbonize in order to meet climatic requirements. To address the need for environmental protection, SAF is said to be one of the viable solutions to cut back on the CO_2 emissions of the sector. However, in a scenario of demand for wide range options for sustainable air travel, questions are continuously arising regarding SAF availability and affordability in terms of production scale, cost, and technology related issues.

1.4 Scope and Limitations

This study focuses on evaluating the potential of SAF to meet future demand for sustainable air travel while addressing associated economic and environmental challenges. The scope includes an in-depth analysis of SAF production technologies, feedstock availability, regulatory frameworks, and the broader economic implications for airlines, passengers, and other stakeholders. The research also considers the role of international organizations, government policies, and market dynamics in promoting SAF adoption and scaling production.

While the analysis benefits from public data and insights from industry stakeholders, certain limitations persist. Access to comprehensive, up-to-date data remains a challenge, particularly regarding closed-door discussions and proprietary information held by private entities or industry groups. This restricts the study's ability to capture the full scope of behind-the-scenes decision-making and nuanced operational details. Additionally, the research relies heavily on existing projections, which are inherently subject to uncertainties, particularly in the context of evolving technologies, geopolitical tensions, and regulatory shifts.

Moreover, while the study examines alternative sustainable aviation solutions such as hydrogen and electric aircraft to contextualize SAF's role in the industry, it maintains a primary focus on SAF due to its current prominence in industry and policy frameworks. Regional variability in feedstock availability, differing regulatory approaches, and competing uses for resources also present challenges to creating a universally applicable model for SAF adoption.

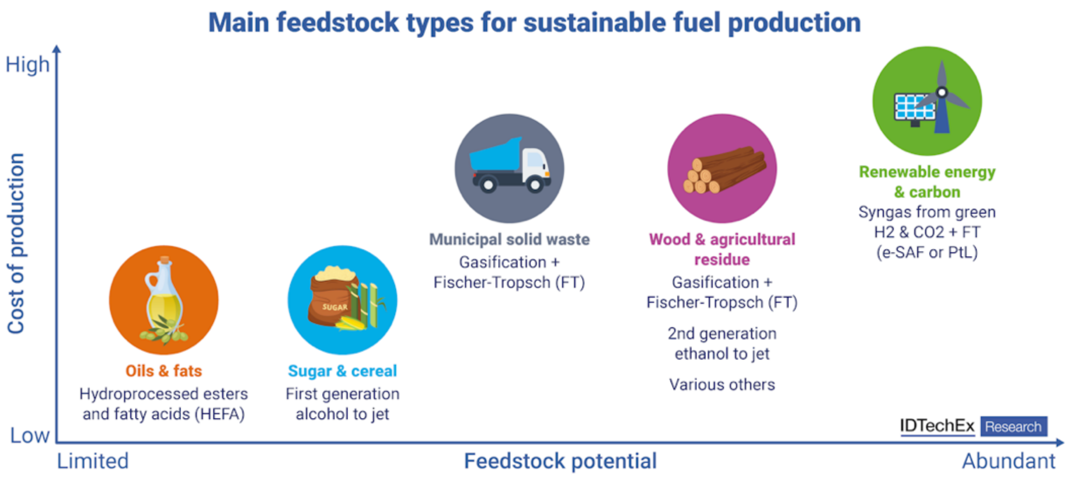
2. Literature Review

2.1 Historical Development and Current State of SAF and Alternative Fuels

2.1.1 Feedstocks and Pathways

The production of SAF begins with one of the five primary categories of raw materials: oils and fats, municipal solid waste (MSW), sugar and cereals, wood and agricultural residue, or carbon and renewable energy. Each category is classified into feedstock type, with the first generation being edible crops and sugars. The second generation of feedstocks includes waste fats, oils and greases (FOG), while the last two generations encapsulate food waste, recycled carbon and other non-biomass materials. Every category of feedstock employs a specific technology for production which must receive approval from the fuel standard body known as the American Society for Testing Materials (ASTM), a globally recognized organization which is a "*leader in the development and delivery of voluntary consensus standards*" (*ASTM*, n.d.), before its commercial deployment. The exhaustive list of authorized feedstocks in the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) framework can be found in Appendix 1.

Figure 1: Types of Feedstocks



(*Sustainable Aviation Fuel - Key Market Drivers and Production Tech*, 2024)

2.1.1.1 Standalone Units

There are two main methods for producing SAF: standalone units and co-processing. Standalone units use sustainable feedstocks in order to produce synthetic kerosene (SK), which is then blended with kerosene to create SAF. The production process for standalone units begins with the conversion of feedstocks in a biorefinery into synthetic kerosene. This SK is then certified according to the relevant appendix in the ASTM D7566 standard which evaluates the technologies, circumstances and characteristics used during the production of SAF. Following the precedent certification, the SK can thereafter be blended with conventional jet fuel at ratios of up to 50% as per the certified blending limit to ensure compatibility with aircraft, engines and fueling systems. The final blended product is certified under ASTM D1655 or Defence Standard 91-091 and is eligibly supplied as conventional Jet A or Jet A-1 fuel (Wright & IATA, n.d.). There are currently eight certified technology pathways to produce SK:

Table 1: Certified Synthetic Kerosene Technology Pathways

Technology	Maximum blend (%v/v)	Feedstocks
FT-SPK & FT-SKA	50	Wastes (MSW, etc.), coal, gas, sawdust
HEFA	50	Vegetable oils: palm, camelina, jatropha and UCO
HH-SPK or HC-HEFA	10	Oils produced from (botryococcus braunii) algae
Synthesized Iso-Paraffin	10	Sugarcane, sugar beet
ATJ (Isobutanol and Ethanol) SPK & SKA	50	Sugarcane, sugar beet, sawdust, lignocellulosic residues (straw)
Catalytic Hydrothermolysis Jet Fuel (CHJ)	50	Waste oils or energy oils

(Wright & IATA, n.d.)

Fischer-Tropsch Hydroprocessed Synthesized Paraffinic Kerosene and Fischer-Tropsch Hydroprocessed Synthesized Kerosene and Aromatics (FT-SPK and FT-SKA aka. PTL)

The synthetic production of hydrocarbons (from ex. coal, natural gas, CO_2) is done through Fischer-Tropsch (FT) reactors. Feedstock is first thermally converted into syngas comprised of H_2 and CO, then transformed into liquid hydrocarbons such as diesel or jet fuel. The FT synthesis includes numerous catalytic processes with either iron or cobalt catalysts¾the choice depending on the desired end product including, but not limited to, gasoline, diesel, or alkanes. The FT process results in the production of synthetic paraffinic kerosene, also known as e-fuel (FT-SPK), allowing blending with typical Jet A or Jet A-1 fuel to a maximum of up to about 50%v/v *(Organización de Aviación Civil*

Internacional, n.d.). The FT-SKA method is substantially the same, with aromatics and paraffinic hydrocarbons included in the compounds, whilst the FT-SPK only includes the latter.

Hydroprocessed fatty acids esters and fatty acids (HEFA)

The HEFA process firstly requires pre-treatment depending on the lipid feedstocks¾such as tallow, algae or plants in order to meet quality standards for the method. The operation continues by deoxygenating, then hydrocracking[2] the oils with Hydrogen and high pressure, transforming the raw material into hydrocarbon chains. The process can convert the bio-based feed into products such as SAF, naphtha and Renewable Diesel, with a differential in intensity when it comes to hydrotreatment, depending on the desired end product. The HEFA method is considered a mature process with limited barriers in the matter of technology, which enables the blending of up to 50%v/v with Jet A or Jet A-1 fuel (*The Basics of SAF Technology | The HEFA Process*, n.d.).

Synthesized Iso-Paraffins (SIP)

The SIP method ferments C6 type sugars including but not limited to, D-glucose, D-fructose and D-galactose, in order to later convert the raw material into a hydrocarbon molecule by hydrotreatment. The end product can fundamentally be blended up to 10%v/v with conventional jet fuel (Wright & IATA, n.d.).

Hydroprocessed Hydrocarbons Synthesized Isoparaffinic Kerosene (HH-SPK or HC-HEFA)

The above method is one of the more recent pathways used in the processing of SAF. It involves the hydrocracking of bio-derived hydrocarbons coming from an algae named botryococcus braunii, and more specifically, its oils. The maximum blend for this specific method is 10%v/v (Rumizen, 2021).

Alcohol-to Jet (ATJ SPK and SKA)

The ATJ process first goes through the dehydration of the alcohol feedstocks, followed by a method called oligomerization, a chemical process which bonds monomers[3] together. The process is then finalized by hydroprocessing. The SPK method converts the alcohol feedstocks into a pure hydrocarbon fuel blending component, with a blending limit of up to 50%v/v, however the SKA (including Aromatics) does not have a maximum blending ratio yet (*SAF Conversion Processes*, n.d.).

[2] Appendix 2: The Hydroprocess
[3] Monomers: a molecule that can be bonded with other identical molecules

Catalytic Hydrothermolysis Jet Fuel (CHJ)

The CHJ process can also be called hydrothermal liquefaction. It encompasses the conversion of acid esters and free fatty acids (FFA) through catalytic hydrothermolysis, followed by processes such as hydrotreatment, hydrocracking, hydroisomerization, and fractionation. The blending ratio for this method is 50%v/v (Wright & IATA, n.d.).

2.1.1.2 Co-Processing

Co-processing involves the simultaneous processing of up to 10% of sustainable feedstocks with fossil feedstocks, all through hydroprocessing in a refinery[4]. The method is increasing in popularity as it addresses the rising demand for SAF with a shorter timeframe and minimal CAPEX. Co-processing enables fuel producers to bring SAF to market quicker while awaiting the development of new specialized processing units, which require substantial investments and long construction timelines (*Co-Processing*, n.d.).

The benefits of co-processing for refineries are numerous. It leverages existing production facilities, hence maintaining economic competitiveness. The pathway also ensures the swift availability of SAF while minimizing investment costs. There are currently three methods authorized under the ASTM D1655 standard to produce SAF:

- Co-hydroprocessing of fatty acid esters and FFA in a conventional petroleum refinery – Max blend ratio of 5%
- Co-processing of hydrocarbons derived from syngas using the FT-SPK/SKA process – Max blend ratio of 5%.
- Co-process of fatty acid esthers and FFA from biomass using the HEFA method – Max blend ratio of 10%

(*Conversion Processes*, n.d.)

However, co-processing faces technological challenges. Even the introduction of small quantities of renewable feedstocks into a hydroprocessing refinery releases linear paraffins from fatty acids. Consequently, refineries run the high risk in modifying the freeze point in jet fuels, compromising the minimum of -40ºC mandated by the ASTM (Co-Processing, n.d.).

[4] Appendix 3: Co-processing

2.2 Policy and Regulatory Framework

The SAF landscape is set to change significantly with newly enforced and upcoming legislation, particularly in the United States and in the European Union. While the United States' current main focus is on reducing SAF costs to increase supply, the European Union takes a different, more broad regulatory approach, including industry targets, blending mandates, and the inclusion of aviation in the European Emissions Trading System (ETS). A detailed overview of the different policies can be found in Appendix 7.

2.2.1 The European Union

The European Union has launched a comprehensive strategy aimed at boosting the production, supply, and use of SAF. The initiative integrates regulatory measures, financial support, research funding, and collaboration within the industry to lower aviation emissions and facilitate a shift towards a more sustainable aviation sector. With these actions, the EU aims to tackle the environmental challenges posed by aviation, establish a reliable market for SAF, and assert its role as a global leader in sustainable aviation.

ReFuelEU Aviation Regulation is an important element that was adopted in October 2023. This regulation sets progressive targets for the use of SAF at EU airports, starting at 2% of total fuel supply by 2025 and increasing to 70% by 2050. Within these general targets, a specified minimum share for synthetic fuels must be met which starts at 1.2% by 2030 and targets 35% by 2050. During the transition period of 10 years, for the first phase, fuel suppliers are to be allowed to comply with the EU's SAF obligations in airports overall over a ten-year period. After 2034, however, individual airports would also be required to have the minimum SAF quotas. The regulation mandates that aircraft operators source at least 90% of their fuel needs from EU airports to avoid practices like fuel tankering[5], which could negatively impact the deployment of SAF. While the regulation does not explicitly require operators to use SAF, it creates a favorable environment where the fuel can be fully expected to develop and grow. There are however some exemptions to this regulatory framework, notably for smaller airports or airports located in remote regions and operators of low-traffic flights. The participation in the change is however highly recommended, which also applies for non-commercial flights. In order to safeguard the environmental integrity of SAF, the regulation makes it conditional on meeting the sustainability criteria laid down in the Renewable Energy Directive

[5] Fuel tankering: a practice where an aircraft carries more fuel than necessary for its safe flight in order avoid refuelling at the destination airport for any following flights

(RED II). Eligible SAF includes biofuels, recycled carbon fuels, and synthetic fuels created from renewable energy. Additionally, the rule allows for the use of low-carbon, non-fossil fuels such as renewable hydrogen, or fuels produced using electricity from nuclear sources. All SAF production and its usage needs to be tracked through the Union Database for traceability purposes.

The EU Emissions Trading System (ETS) was launched in 2012 and complements the ReFuelEU in encouraging the adoption of SAF. Under the ETS, airlines flying within the European Economic Area (EEA) must obtain allowances for their CO_2 emissions, and since SAF is classified as "zero-rated," it is therefore exempt from this requirement. The ETS also promotes SAF adoption by providing around EUR 1.6bn that has been set aside from ETS revenues to help bridge the price gap between SAF and traditional jet fuel. These funds are allocated on a first-come, first-served basis, giving priority to airlines covering ETS routes. Additionally, support for up to 100% of the price difference between SAF and conventional jet fuel is available for flights departing from smaller or remote airports, as their size and/or location typically incur higher SAF costs. The ETS also features a EUR 400m Innovation Fund aimed at backing projects that enhance SAF technologies, renewable energy, and hydrogen development. Additionally, SAF has been included in the EU taxonomy, improving access to green finance and encourages investment in sustainable aviation projects (*ICAO Guidance on Policy Measures for SAF Development and Deployment*, n.d.-a).

The Renewable Energy Directive (RED II) also imposes stringent sustainability criteria on biofuels to mitigate environmental and climate-related impacts. As of 2021, most biofuels consumed in the EU were derived from food crops, such as biodiesel from rapeseed, sunflower, palm, and soy oils, and bioethanol from corn, wheat, sugar beet, barley, and rye. This widespread reliance on crop-based biofuels across multiple sectors further limits the availability of feedstocks for SAF production (Commission Delegated Regulation (EU) 2019/807, 2019)

Feedstock availability is expected to face additional pressures with the EU-wide ban on palm oil for biofuels, set to take effect in 2030. Palm oil, once viewed as a key solution to combating climate change, has faced significant criticism for its role in deforestation. The ban shifts focus to alternative crops like rapeseed and soybeans grown in Europe. However, these alternatives present their challenges. For instance, rapeseed produces significantly less oil per unit of land compared to palm oil and requires more fertilizers and pesticides, which can strain resources and raise sustainability concerns. Additionally, these crops store less CO_2 than palm plantations, diminishing their overall environmental benefits (*The EU Wants to Phase out Palm Oil from Biofuels. Here's Why That Might Be a Bad Idea | World Economic Forum*, n.d.).

Biofuels with properties similar to petroleum distillates include biodiesel, renewable diesel, renewable jet/aviation fuel, and renewable heating oil. This competition for feedstocks extends beyond the aviation sector. For example, the shipping industry is introducing measures to increase its use of renewable fuels. The FuelEU Maritime Regulation (Regulation (EU) 2023/1805), effective from January 1, 2025, promotes renewable, low-carbon fuels and clean energy technologies for ships. It requires commercial vessels over 5,000 gross tonnage operating in EU ports to reduce emissions from marine fuels (bunker fuels) or face penalties. This regulation follows the inclusion of shipping in the EU ETS in 2024, which requires ships to pay for emissions related to voyages involving EU ports. These regulatory frameworks further illustrate the increasing competition for feedstocks among multiple industries, adding to the challenges of scaling SAF production (Tunagur, 2025).

2.2.2 The United States of America

The United States 2021 Aviation Climate Action Plan was launched on November 9, 2021, and outlines a comprehensive policy framework aimed at achieving the U.S. Aviation Climate Goal of "*Net-Zero GHG Emissions from the U.S. Aviation Sector by 2050*" (*ICAO Guidance on Policy Measures for SAF Development and Deployment*, n.d.-a). The framework emphasizes the importance of SAF for the long-term decarbonization of the aviation industry. The U.S. government is dedicated to collaborating with the industry to swiftly boost SAF production through various policy measures, including the "SAF Grand Challenge" – a wide-ranging initiative by the U.S. government to enhance SAF availability to meet the fuel requirements of U.S. aviation by 2050. In order to scale up SAF production, the U.S. aims to produce at least 3bn gallons of SAF per year by 2030. By 2050 their aim is to meet 100% of aviation fuel demand, projected to be around 35bn gallons per year (*ICAO Guidance on Policy Measures for SAF Development and Deployment*, n.d.-a).

The U.S. Department of Transportation (DOT), Department of Energy (DOE), and Department of Agriculture (USDA) are leading the SAF Grand Challenge which focuses on reducing costs, enhancing sustainability, and expanding SAF production and use. The initiative was announced at a White House Roundtable on Sustainable Aviation on September 9, 2021, emphasizing the importance of U.S. executive branch agencies working collaboratively to support research, development, demonstration, and deployment of SAF. Additionally, the plan recognizes the need for economic incentives, including blender's tax credits and investment tax credits, to bridge the cost gap between SAF and conventional jet fuel.

Through the SAF Grand Challenge, the U.S. DOE, DOT, and USDA are projected to work with the U.S. Environmental Protection Agency (EPA) and other agencies to enable a government-wide commitment which is to leverage existing activities in research, development, demonstration, and deployment. The initiative will also likely accelerate new research and technology advancements while implementing a supporting policy framework where the aim is to meet objectives such as expanding SAF supply and end use, reducing production costs, and enhancing sustainability.

The U.S. DOE, DOT, and USDA also lead an interagency team in the scope of the developed the SAF Grand Challenge Roadmap, which was released on September 23, 2022 and is titled "*Flight Plan for Sustainable Aviation Fuel*" (*ICAO Guidance on Policy Measures for SAF Development and Deployment*, n.d.-a). The precedent outlines six key action areas:

- Feedstock Innovation
- Conversion Technology Innovation
- Building Supply Chains
- Policy and Valuation Analysis,
- Enabling End Use
- Communicating Progress and Building Support.

(*ICAO Guidance on Policy Measures for SAF Development and Deployment*, n.d.-a)

Notably, in August 2022, the U.S. Congress further supported SAF production through the Inflation Reduction Act (IRA). This included three provisions to incentivize SAF development:

Table 2: U.S. Provisions Set to Incentivize SAF Development

Provision	Framework
Sustainable Aviation Fuel Credit (SAF blenders tax credit)	Provides a starting incentive of USD 1.25 per gallon of SAF with at least a 50% lifecycle greenhouse gas improvement compared to conventional jet fuel. This credit increases to USD 1.75 per gallon as emissions reduction improves, in effect from 2023 to 2024.
Clean Fuel Production Credit	Set to begin in 2025 and extend through 2027. This provides a credit up to USD 1.75 per gallon for SAF, enhancing its value relative to ground transportation fuels.
Alternative Fuel and Low Emission Aviation Technology Program	Establishes a competitive grant program for projects related to SAF production, transportation, blending, or storage. The grant program, FAST (Fueling Aviation's Sustainable Transition), allocates approximately USD 250m for projects, with first grants expected in 2024.

(*ICAO Guidance on Policy Measures for SAF Development and Deployment*, n.d.-a)

2.2.3 Other Countries' SAF Policies

Japan is driving the development and adoption of SAF through a multilateral approach that includes public-private partnerships and a regulatory framework, aiming to replace 10% of aviation fuel with SAF by 2030. In order to meet CORSIA standards and compliance, various working groups have been established and incentives put in place, including CAPEX subsidies, tax exemption for feedstocks imports and funding for technology Research & Development (R&D). Japan also plans to introduce tax credits proportional to SAF production volumes and use Green Transition Bonds in order to magnify the change (*ICAO Guidance on Policy Measures for SAF Development and Deployment*, n.d.-a).

Brazil has proposed a comprehensive policy emphasizing CO_2 reduction mandates for airlines, R&D funding, and certification standards aligned with ICAO. The policy avoids blending mandates and encourages competition and efficient SAF technologies. Meanwhile, India has set incremental SAF blending targets for international flights, starting at 1% in 2027 and rising to 5% by 2030. When it comes to Singapore, their Sustainable Air Hub Blueprint mandates 1% SAF usage for flights from

2026, with plans to increase this to 3-5% by 2030 (*ICAO Guidance on Policy Measures for SAF Development and Deployment*, n.d.-a).

2.2.4 International Energy Agency

The International Energy Agency (IEA) is an autonomous intergovernmental organization that serves as a global authority on energy policy. It was established in 1974 in response to the oil crisis to promote energy security among its member countries, and more recently, a sustainable energy future.

The Net Zero Emissions by 2050 Scenario by IEA outlines a strategic pathway for the global energy sector to achieve net CO_2 emissions by 2050, with advanced economies reaching this milestone ahead of others. This scenario also aligns with key energy-related Sustainable Development Goals, including achieving universal energy access by 2030 and significantly enhancing air quality worldwide. The approach emphasizes a coordinated and secure transition, aiming to maintain energy stability through policies and incentives that enable stakeholders to adapt to the required changes. The focus is on minimizing market disruptions, all while reducing the risk of stranded assets. A key element of this pathway is the widespread adoption of clean energy technologies and improvements in energy efficiency. The scenario is underpinned by a full analysis of project timelines for critical mineral supplies and clean energy technologies to ensure its feasibility. Nevertheless, potential bottlenecks in supply chains for certain technologies underscore the need to prioritize material reuse, recycling, and efforts to reduce the material demands of clean energy solutions (*Net Zero Emissions by 2050 Scenario (NZE) – Global Energy and Climate Model – Analysis*, n.d.).

2.3 Comparative Analysis of Alternative Fuels and Solutions

The decarbonization of the aviation sector requires a comprehensive exploration of alternative fuels and technologies beyond SAF. This section examines and evaluates other potential solutions, such as hydrogen or electric propulsion systems. By comparing multiple elements, this analysis aims to provide a balanced perspective on how these alternatives might complement or compete with SAF in reducing aviation's carbon footprint.

2.3.1 Hydrogen

Hydrogen in its liquid form (LH_2) is a promising alternative to kerosene. It contains about 2.5 times more energy per kilogram than kerosene and produces only water vapor when burned, as it does not contain any carbon. Hydrogen combustion also reduces NO_x emissions by up to 90% and eliminates particulate matter, resulting in an improved local air quality. Both aforementioned elements showcase the potential of the product in the future of sustainable air travel. The implementation of LH_2, however, has its challenges. Its energy per mass is elevated, but contains a low volumetric density. This means that it requires about four times more storage space than kerosene, necessitating significant redesigns of aircraft (*IATA Hydrogen Factsheet*, n.d.).

H_2 has an invisible flame and of an odorless nature, which can complicate leak detection and firefighting. As a small molecule, hydrogen can escape through tiny cracks or pores, further increasing the risk of undetected leaks. It is therefore critical to install proper insulation and robust containment systems to ensure its safe use (*IATA Hydrogen Factsheet*, n.d.).

There has been significant development regarding LH_2 in the transporting sector since 2018, and more particularly in the automotive sector. When it comes to aviation, the U.S. DOE has allocated USD 47.7m for 16 research, development, and demonstration (RD&D) projects to advance clean hydrogen technologies (*U.S. Department of Energy 2023*, n.d.). Hydrogen fuel cells are also being explored as a potential replacement for auxiliary power units (APUs) or as a source of in-flight power for systems such as control surfaces and landing gear retraction. Flight demonstrations have already been done by full-sized aircraft powered by liquid hydrogen (*IATA Hydrogen Factsheet*, n.d.).

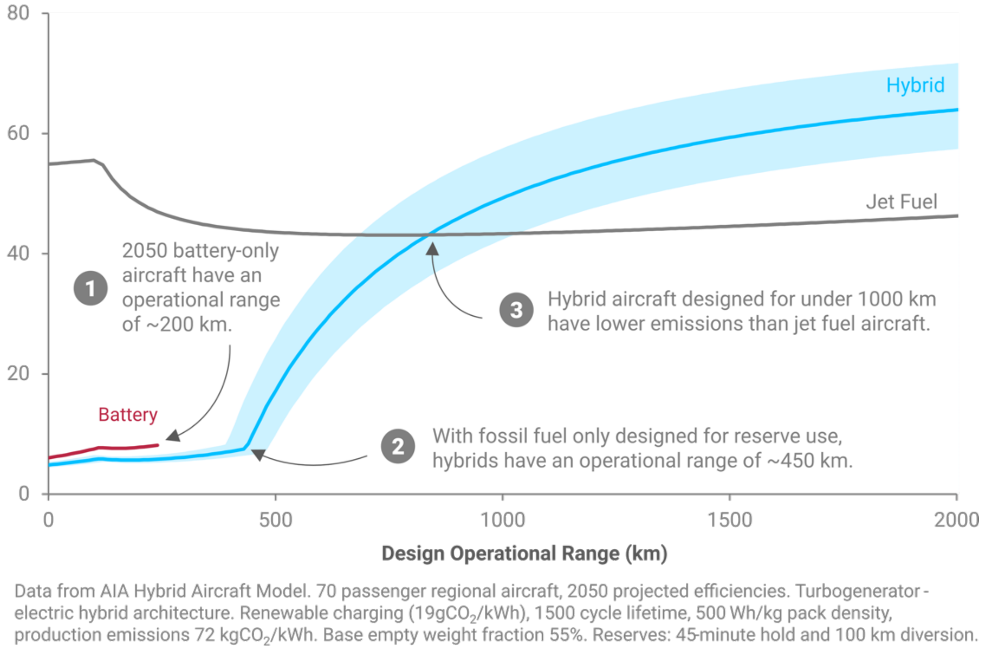
2.3.2 Battery and Hybrid-powered Aircraft

Electrification has been a key strategy in tackling the decarbonization of the automotive industry and is currently being explored as a potential pathway for aviation. Battery-powered flights use stored energy in batteries to power electric motors for propulsion. Similarly to liquid hydrogen-powered aircraft, electrification eliminates in-flight emissions of carbon dioxide and other harmful gases. However, in the case of electrification, GHGs can still be emitted during battery production and electricity generation. Hence, sustainable sources of electricity must be used to charge batteries and support sustainable manufacturing practices to ensure that the process remains environmentally friendly, reducing overall emissions in comparison to conventional jet fuel.

Battery-powered aircraft are facing challenges, particularly due to the weight of today's batteries, nearly 50 times heavier than an equivalent amount of jet fuel. Aircraft must carry more battery capacity than needed for a journey to ensure safety in case of diversions. The extra weight reduces the distance aircraft can travel and for short hauls, the additional weight significantly impacts fuel efficiency (Gribbin & Singh, 2024). Hybrid aircraft offer a more promising solution to the aforementioned challenges. They combine battery power with another energy source, such as hydrogen or fossil fuels in order to enhance performance.

Currently, hybrid-electric aircraft are predominantly developed for short-haul flights with ranges below 500 km, accounting for a small portion of global passenger emissions. As battery technology improves, hybrid-electric planes could expand into the short-haul market (up to 1,500 km), which represents a significant portion (33%) of global passenger emissions. The medium and long-haul markets are currently out of reach for this technology (Gribbin & Singh, 2024).

Figure 2: Projected Emissions and Range for Battery and Hybrid-powered Aircraft in Comparison to Conventional Jet Fuel



(Gribbin & Singh, 2024)

Ultimately, hybrid-electric aircraft can play a critical role in reducing emissions for short-haul flights and combined with other sustainable practices during the production of batteries, as well as the use of alternative fuels, could help the aviation industry achieve its decarbonization goals and move towards net zero emissions.

2.3.3 Liquefied Methane (LNG)

Liquefied natural gas (LNG), predominantly composed of methane, has emerged as a potential alternative to conventional jet fuel for aviation. Liquefaction significantly reduces the fuel's volume and weight, making it more practical for aircraft applications. However, the implementation of LNG faces critical logistical and safety challenges. Airports would need infrastructure upgrades, such as large storage tanks and liquefaction facilities, as well as robust safety measures to handle LNG's cryogenic properties. Even though LNG combustion produces less CO_2 than traditional jet fuel due to its higher hydrogen content, methane's greenhouse gas properties pose a significant challenge. Even a small escape or incomplete combustion (less than 1%) could cancel its CO_2 reduction benefits. Addressing methane leakage is therefore critical when it comes to LNG's viability as a fuel (Rompokos et al., 2020).

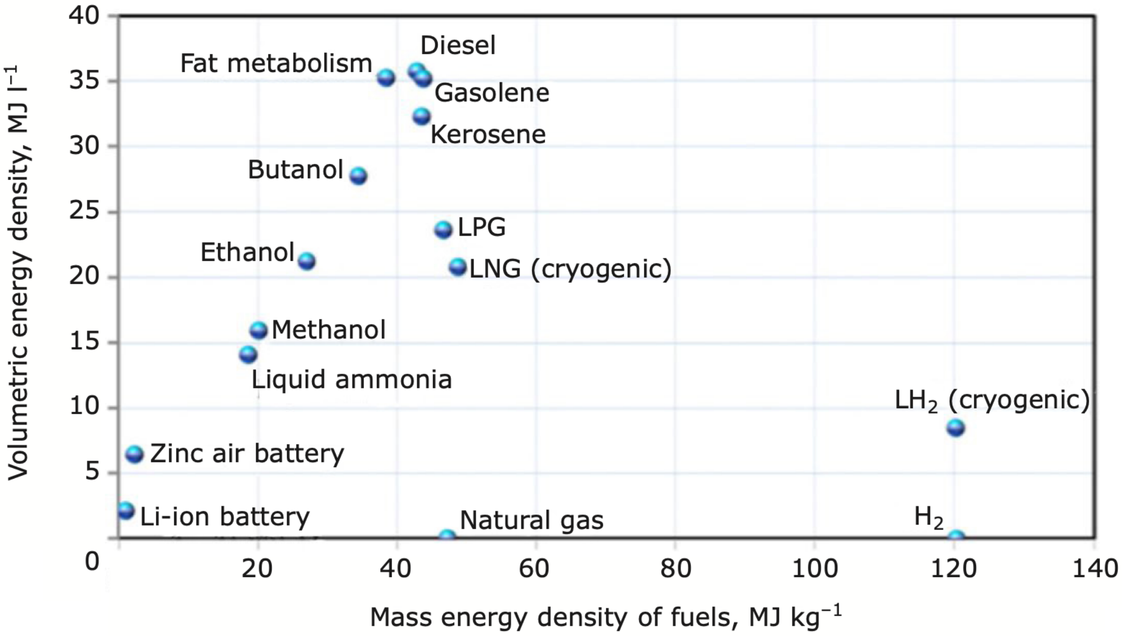
2.3.4 Liquefied Ammonia

Ammonia is a widely traded commodity and is primarily used in agriculture and plastics, with limited current use as a fuel. Ammonia and ammonia/hydrogen blended fuels are currently at a low technology readiness level, though showing promise as a pathway forward. Relatively lower infrastructure changes are required for ammonia compared to hydrogen, which makes it an appealing option for transport and storage. However, H_2 offers a higher gravimetric energy density and broader fuel cell applications, providing a notable advantage for flight operations. Despite these advantages, ammonia production is currently associated with high carbon emissions, necessitating a transition to 'green' ammonia, which can be produced using renewable energy (*Fullonton, A., Jones, C., and Larkin, A., 2023*, n.d.).

2.3.5 Comparison of Alternative Fuels

The below Figure highlights the comparison of the aforementioned alternative fuels by showcasing the volumetric energy density on mass energy density, giving a clearer picture of the different solutions in comparison to kerosene.

Figure 3: Comparison of Multiple Energy Sources in Aviation



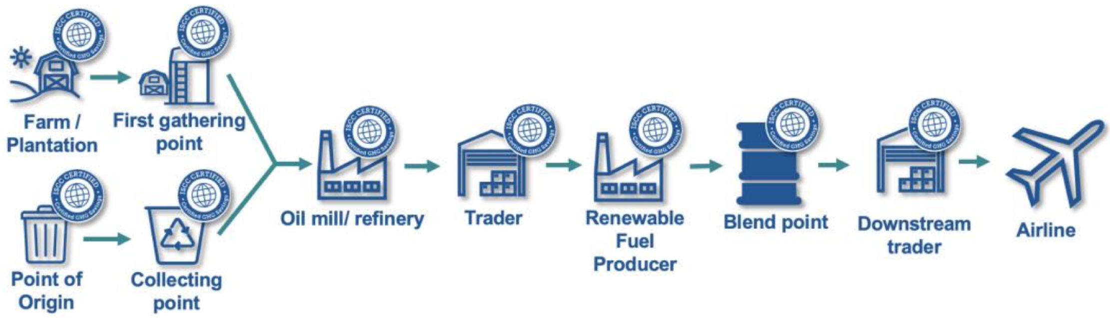
(Bauen et al., 2020)

Whilst liquefied methane and liquefied ammonia may ultimately be considered as SAF, they pose a threat to current solutions to decarbonize the industry. In their current development stage, batteries are not yet suitable for widespread use in larger commercial aircraft, which is mainly due to their substantial weight, significantly reducing fuel efficiency and ultimately, the range. Nonetheless, hybrid-powered aircraft can be considered as complementary to existing SAF solutions. When it comes to liquid hydrogen, it does pose a threat to SAF on the long-term as new fleet of aircraft make their way onto the market supporting the use of LH_2.

2.4 Sustainability and Traceability in SAF Supply Chains

SAF supply chains involve a diversity of activities such as feedstock cultivation, logistics and distribution, processing, and refining of primary ingredients, intermediates, as well as finished products. Such supply chains are often intricate and global, including sustainable as well as non-sustainable elements at various locations of the chain. The proper verification of its traceability, as well as the clear description of the supply chain is of high importance when it comes to SAF. Hence, it is necessary that each participant or economic operator is certified independently, and regular audits take place to check adherence to sustainability, traceability, chain of custody, and GHG calculations.

Figure 4: Simplified ISCC Certified Supply Chain



(McCausland & Malvyn, n.d.)

2.4.1 Certifications

Certifications have been introduced in order to monitor the renewables sector. For instance, ISCC is a globally recognized sustainability certification system that encapsulates a wide range of sustainable feedstocks, including agricultural and forestry biomass, biogenic wastes and residues, circular materials, and renewables. ISCC has issued more than 9,000 valid certificates in more than 130 countries, for this reason, it is one of the largest certification systems worldwide (*ISCC Guidance Document Proof of Compliance V1.0*, n.d.). Under ISCC, economic operators throughout the renewable fuel supply chain are certified to ensure traceability from feedstock origin and production to the supply of the finished product to the market. This requirement is aligned with major regulatory frameworks such as EU RED II and other EU legislative initiatives, including the EU ETS and ReFuelEU Aviation. Sustainability information such as compliance with sustainability and GHG emissions savings criteria is passed along the supply chain from one certified economic operator to another through sustainability documents. These documents include Sustainability Declarations, issued for raw materials and intermediate products, and Proofs of Sustainability (PoS), issued for final products.

In the case of absent PoS documentation, the Proof of Compliance (PoC) framework has been developed and serves several purposes:

- Providing a standardized structure for the forwarding of documentary evidence to end users, including aircraft operators and shipping companies, in situations where PoS documentation is unavailable.
- Offering a document similar to the PoS, demonstrating compliance with sustainability criteria and GHG emissions.
- Incorporating a robust auditing system, ensuring that the issuance and forwarding of the document are accurate and compliant.

However, ISCC does not guarantee the acceptance of PoC documents under specific regulatory frameworks, as is it still under the jurisdiction of competent authorities. Therefore, economic operators are advised to confirm the acceptance of PoC documents the with the respective authorities. Moreover, even though PoC documents can be used for non-regulated market claims, the managerial ramifications of such usage need to be carefully addressed, especially in the case of a prior submission of the original PoS documentation (ISCC Guidance Document Proof of Compliance V1.0, n.d.).

Despite these certification efforts, concerns over fraudulent practices and insufficient traceability persist. As highlighted by an investigation made in 2023, a third of UCO in the market is likely fraudulent, with virgin palm oil being labeled as waste feedstock. Suspiciously high collection rates have been reported in regions such as Saudi Arabia, Kuwait, and Bulgaria. For example, it was claimed that Malta's population collected an implausible three liters of used cooking oil per person per day in 2022, compared to more realistic figures of five liters per person annually in Belgium and the UK (Norways et al., 2023).

These discrepancies underscore the urgent need for auditing and enforcement mechanisms to ensure that SAF supply chains remain genuinely sustainable and transparent. Without addressing such issues, the credibility and environmental benefits of SAF risk being undermined, jeopardizing its role as a pillar of aviation's sustainable future.

2.4.2 Traceability of GHG Emissions During the Lifecycle of the Product

The combustion of drop-in SAF generates comparable emissions to those of fossil-based jet fuels, aside from minor efficiency improvements. Consequently, the majority of GHG emissions reductions associated with SAF arise from its production process. In order to evaluate the overall climate benefits of SAF, a Lifecycle Analysis (LCA) is conducted. This comprehensive assessment accounts for all stages in the lifecycle of aviation fuels, including feedstock recovery and transportation, fuel production and distribution, and fuel consumption by aircraft. These values are compared to the baseline emissions of fossil-based jet fuels to calculate the overall GHG emissions reduction. The complexity of LCA arises from the numerous variables, such as the origin and type of feedstock, electricity mix, and production methods, all of which significantly impact total GHG emissions (*How Sustainable Are SAF?*, n.d.).

The production process and feedstocks for SAF generally result in very low levels of sulfur and aromatic compounds, which contribute to both volatile and non-volatile particulate matter (PM) emissions. Research on SAF blends with fossil-based jet fuel has demonstrated significant reductions in PM emissions at cruising altitudes, ranging from 50% to 97% compared to conventional jet fuels. The greatest reductions are observed at low engine power settings, such as during taxiing. Due to their distinct physicochemical properties, SAF drop-in fuels can positively impact air quality near airports and mitigate climate effects by reducing contrail-cirrus cloud formation—provided the sulfur and aromatic content of the fossil fuel component in the blend does not counteract these benefits (*How Sustainable Are SAF?*, n.d.).

Land use impacts are a notable concern for certain aviation biofuels. Direct Land Use Change (DLUC) occurs when existing farmland is repurposed for biofuel feedstock cultivation, while Indirect Land Use Change (ILUC) arises when biofuel demand drives land expansion elsewhere, potentially converting high-carbon-stock ecosystems like forests. Such activities, including deforestation, can release substantial amounts of stored CO_2 from trees and soil. ILUC impacts are complex to estimate and depend on intricate modeling, with results varying widely (*How Sustainable Are SAF?*, n.d.).

To address these challenges, the EU's RED II imposes restrictions on biofuels derived from food and feed crops. Their contribution to EU Member States' renewable energy targets for transport is capped, particularly when significant expansion onto high-carbon-stock land is observed, with a phase-out planned by 2030. Similarly, biofuels from food and feed crops are ineligible under the proposed ReFuelEU Aviation initiative for the same sustainability concerns.

3. Methodology

This section outlines the methodology employed in the research, detailing the approach, methods, and techniques used to collect and analyze data. It provides a comprehensive explanation of how the research was conducted, ensuring the reliability and validity of the findings. The methodology section addresses key considerations such as research design, data collection methods, sample selection, and analytical techniques, allowing for a clear understanding of how the study was carried out and how conclusions were drawn.

3.1 Research Design and Theoretical Framework

The research begins with a comprehensive analysis of relevant materials, including academic studies, official documents, and reports from industry organizations. This step is essential for situating the topic of SAF within its theoretical and practical framework, providing a solid understanding of its development and role in the aviation sector. By critically reviewing these sources, the study will identify gaps in the existing body of knowledge and ensure that the research builds upon established work. This analysis not only contextualizes the subject but also highlights areas where further investigation is necessary.

Subsequently, the study will employ a case study to analyze the leading SAF supply company, Neste, including its efforts to develop the products and its challenges. Additionally, interviews with experts in the sector will be conducted to enrich the case study findings with practical insights. This study will offer a clearer understanding of how the industry is working to overcome barriers and achieve compliance with global and regional frameworks.

In addition, the study will incorporate an economic analysis to assess the broader implications of SAF adoption on the aviation sector and related markets. This analysis will involve evaluating data on production costs, feedstock availability, lifecycle emissions, and market trends. Comparative methods will be applied to assess the impact of SAF deployment on airline operations and global emissions reduction targets. By grounding the findings in empirical evidence, this approach will provide a comprehensive view of the economic viability and environmental benefits of SAF, offering actionable insights into its potential as a pillar of sustainable air travel. Together, these methodologies ensure a balanced and rigorous investigation into SAF development, addressing its technical, economic, and environmental dimensions.

3.2 Validity and Reliability

This thesis maintains validity and reliability by applying recognized research methods, using verified data sources, and documenting each step transparently. These measures help ensure that the results accurately reflect the study's focus and can be reproduced under similar conditions.

4. Meeting Future Demand for Sustainable Air Travel

As the demand for air travel continues to grow, the aviation industry faces increasing pressure to adopt sustainable solutions to reduce its environmental impact. Sustainable Aviation Fuels have shown promise in reducing greenhouse gas emissions compared to traditional jet fuels. However, scaling up SAF production and integrating these fuels into existing aircraft and infrastructure remains a significant challenge. This section examines how current technologies and advancements in SAF development are helping meet the future demand for sustainable air travel.

4.1 Forecasted Growth in Air Traffic

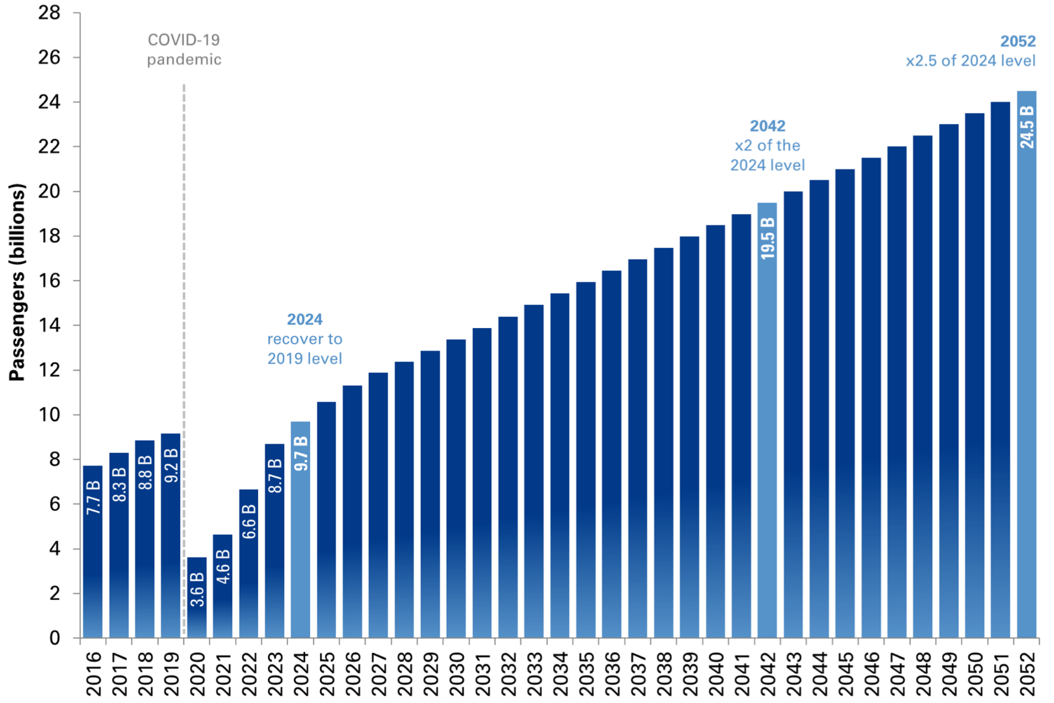
The growth of air traffic is a critical factor influencing the demand for SAF and the broader decarbonization of the aviation sector. Understanding the forecasted expansion of global air travel provides key insights into the scale of emissions challenges and the corresponding need for sustainable solutions.

4.1.1 Passenger Traffic

Between 2024 and 2042, global passenger traffic is projected to expand at a compound annual growth rate (CAGR) of 3.96%. A steep recovery is anticipated in the initial three years (2023–2026), with a 9.1% CAGR, before growth converges to a pre-COVID-19 rate of 3.36% for the period 2024–2052. By 2042, worldwide passenger traffic is expected to reach nearly 20bn—twice the projected level for 2024. Looking ahead to 2052, traffic is forecasted to reach 24.5bn, amounting to approximately 2.5 times the 2024 projection.

More specifically, the international passenger market made a strong recovery in 2023, reaching an estimate of 4.5bn passengers—a 41.6% year-on-year (YoY) increase versus 2022 (IATA, n.d.). In 2024, international passenger traffic is projected to have risen to approximately 4.9bn (*Airline Industry - Passenger Traffic Worldwide 2024*, n.d.). Meanwhile, domestic passenger traffic rose by 30.4% in 2023, slowing to 5.7bn in 2024 (10% YoY growth) (*WATF*, n.d.). Over the longer term, domestic passenger traffic is projected to expand at a 3.8% CAGR between 2023 and 2042. By 2042, international passengers are anticipated to account for 45% of total traffic, rising to 46% by 2052 (WATF, n.d.).

Figure 5: Long-term Global Passenger Traffic Forecast



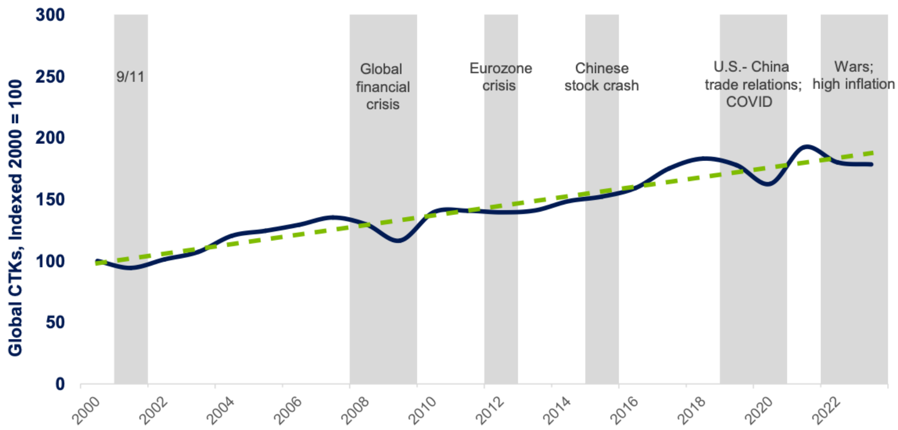
(*ACI World Airport Traffic Forecasts 2023-2052*, n.d.)

Additionally, the global passenger market is expected to shift from advanced economies to emerging and developing economies on the long run. Between 2023 and 2042, advanced economies are projected to grow at a CAGR of 3.2%, while emerging and developing economies are anticipated to expand more robustly at 5.4%. By 2042, China is projected to overtake the United States as the largest passenger market, maintaining its position through 2052. Emerging economies, such as Indonesia, Vietnam, and the Philippines, are expected to rise significantly in the rankings, showcasing their increasing prominence in the global aviation sector. Conversely, traditional leaders such as Germany, France, and Canada are projected to see a relative decline in their rankings, emphasizing the shift in market dynamics from advanced to emerging economies (WATF, n.d.).

4.1.2 Air Freight Traffic

The air cargo market encountered notable challenges in early 2023 due to global economic uncertainty but showed a robust recovery in the latter half of the year, fueled by rising demand for Chinese e-commerce goods. Consequently, the market reached a volume of 113m metric tonnes (MT) in 2023, reflecting a decrease of 3.1% YoY (-4.6% versus 2019) (*ACI World*, 2024). While recent fluctuations highlight short-term volatility, the industry has consistently demonstrated long-term resilience. Over the past two decades, despite periodic downturns, the sector has maintained an average annual growth rate of 2.6%.

Figure 6: Air Cargo Market Resilience



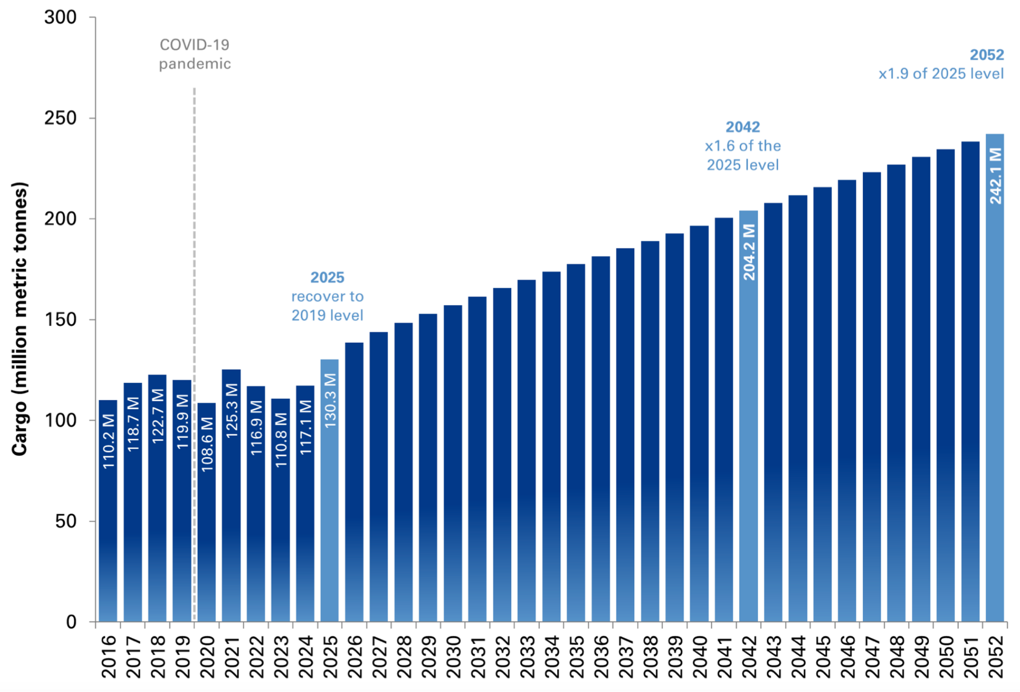
CTK is a measurement of actual cargo traffic, calculated by multiplying the tonnage of freight carried by the distance

(*Boeing-WACF-2024.Pdf*, n.d.)

By end of 2024, global air cargo volumes are expected to have rebound, growing to approximately 117m MT with a year-on-year increase of 3.6%. Over the long term, global air cargo is anticipated to expand at a CAGR of 3.1% from 2024 to 2042 and 2.6% from 2024 to 2052 (*ACI World Airport Traffic Forecasts 2023-2052*, n.d.).

Supply chain diversification is a key driver of future air cargo growth. The COVID-19 pandemic and rising geopolitical risks have highlighted the vulnerabilities of single-source supply chains, such as labor shortages, shipping delays, and manufacturing disruptions. In response, manufacturers have increasingly diversified their operations across other parts of Asia, particularly in Southeast Asia. Since 2017, these countries have significantly enhanced their industrial capacities and global air export volumes. As distributed supply chains become more common, air cargo will play a vital role in ensuring reliable and timely connectivity across various stages of the manufacturing process (*Boeing-WACF-2024.Pdf*, n.d.).

Figure 7: Long-term Global Air Cargo Traffic Forecast



(ACI World Airport Traffic Forecasts 2023-2052, n.d.)

Additionally, the growth of e-commerce and express networks is expected to further boost air cargo demand. The entry of new players in the e-commerce sector significantly accelerated air cargo activity in late 2023 and into 2024, underscoring its critical role in serving the fast-paced digital economy. With global e-commerce revenues projected to grow by approximately 9% annually through 2029—led by emerging markets in South Asia and Southeast Asia—air cargo networks will be indispensable in supporting this expansion (Boeing-WACF-2024.Pdf, n.d.).

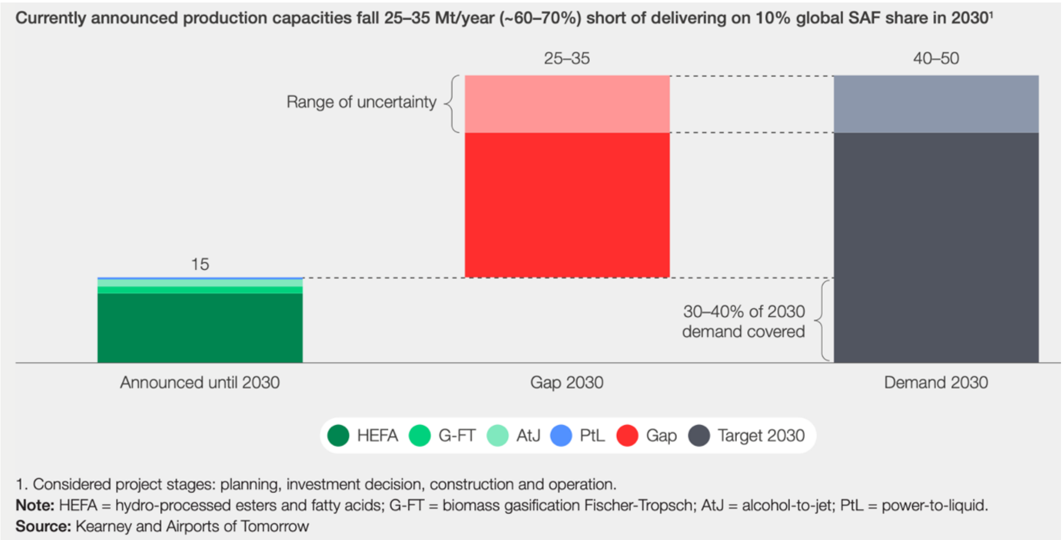
4.2 SAF Production Capacity and Scalability

Over the next five years, SAF production is expected to be dominated by the HEFA pathway, which is projected to account for 85% of total SAF output. This reliance on HEFA is primarily due to its proven technology and the ease of converting waste fats, oils, and grease into fuel. However, these feedstocks are limited, representing a critical challenge for scaling SAF production. In 2024, SAF production volumes reached 1m MT (1.3bn liters), double the 500k MT (600 million liters) produced in 2023. Despite this progress, SAF only accounted for 0.3% of global jet fuel production and 11% of global renewable fuel output, significantly falling short of earlier projections which had anticipated SAF production for 2024 to hit 1.5m MT (1.9bn liters) (IATA Press Release, 2024). The majority of renewable fuels were allocated to other sectors such as road transportation and industrial applications, emphasizing the critical need for targeted policies and strategies to elevate SAF's role within the renewable fuel landscape (IATA Press Release, 2023).

Compounding this challenge, key SAF production facilities in the United States have postponed their production scale-up to the first half of 2025. Looking ahead to 2025, SAF production is projected to increase to 2.1m MT (2.7bn liters), representing 0.7% of global jet fuel production and 13% of renewable fuel capacity worldwide (IATA Press Release, 2024). The scale of the challenge becomes evident when considering that 17.5bn liters (around 15m MT) of SAF will be required annually by 2030 to meet the ambitious climate targets set by international agreements.

Current project announcements account for only 30–40% of the estimated 10% global SAF demand share projected for 2030, with the majority relying on HEFA-based production as can be seen in the Figure below:

Figure 8: Currently Announced Production Shares



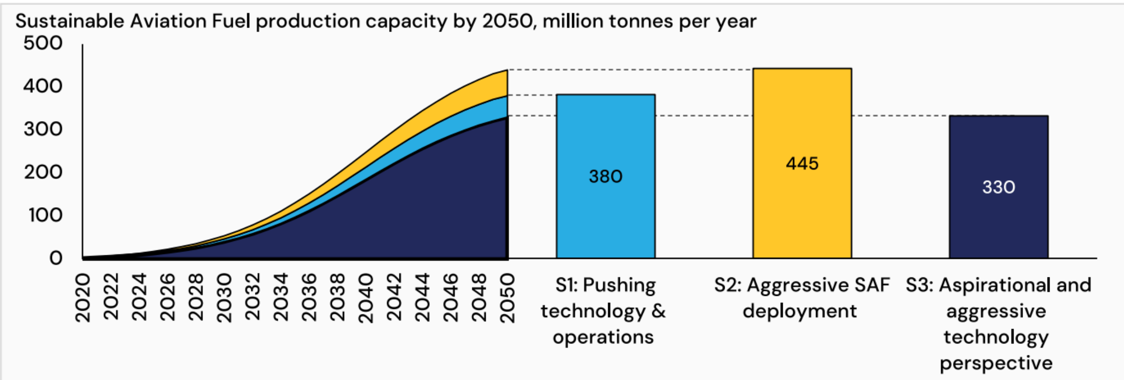
(Baroutaji et al., 2019)

One such milestone was the global framework established at the Third Conference on Aviation Alternative Fuels (CAAF/3), hosted by the ICAO, which aims to make fuels used in international aviation 5% less carbon-intensive by 2030. To achieve this, governments must introduce robust policies that incentivize renewable fuel producers to allocate 25-30% of their output to SAF. Such measures could include financial incentives like tax credits or subsidies, renewable fuel blending mandates, and investments in infrastructure and R&D to expand feedstock availability and streamline production technologies.

The SAF industry also requires diversification of production pathways to reduce dependency on HEFA and address feedstock limitations. IATA has emphasized three critical areas: scaling up certified pathways such as ATJ and FT, accelerating research into alternative methods, and improving feedstock conversion technologies. In the United States, significant infrastructure investments are underway to scale HEFA production, supported by federal and state incentives. Air Transport Action Group (ATAG)'s identified scenarios offer a framework to assess the previously discussed pathways for scaling SAF:

- Scenario 1 focuses on advancing current technologies and improving operational efficiency to gradually reduce emissions.
- Scenario 2 emphasizes rapid investment and expansion of SAF production, supported by strong policy measures, infrastructure development, and industry collaboration.
- Scenario 3 envisions a transformative future combining breakthrough innovations and bold strategies to achieve significant decarbonization.

Figure 9: Projected SAF Production Capacity (mMT/year)



(*ICF Report 2021.Pdf*, n.d.)

The most ambitious scenario (S2) estimates SAF production capacity at 445m MT per year by 2050, while S1 and S3 project capacities of respectively 380m MT and 330m MT. These scenarios highlight the varying levels of technological advancement, policy implementation, and operational efficiency.

The scalability of SAF needs to ramp up significantly in order to meet these projections, considering the current production. Even so, ISCC's predictions sit even higher with a needed production of 449 MT per year at least by 2050 (Boyd, n.d.).

Additionally, to achieve the required scale of SAF production and adoption, cross-sector collaboration among governments, fuel producers, airlines, and other stakeholders is essential. This includes addressing technical challenges such as feedstock availability and optimizing production methods while implementing regulatory measures to promote SAF. By aligning global efforts and leveraging innovative solutions, the aviation sector can significantly reduce its carbon footprint and contribute to a sustainable energy transition.

4.2.1 Competing for Feedstocks

As previously mentioned, SAF is in a competitive race for access to renewable fuel feedstocks, with multiple sectors contending for the same limited resources. The aviation sector is projected to access only between 41% to 55% of the total SAF required due to this intense competition for bioenergy. Some estimates indicate that aviation could secure at least 180m MT of SAF annually (*ICF Report 2021.Pdf*, n.d.). Fuels with properties comparable to distillates such as biodiesel, renewable diesel, renewable jet fuel, and renewable heating oil are in high demand, further intensifying this competition.

Existing regulatory frameworks remain fragmented, creating a patchwork of measures to support SAF production and usage, and historically, these regulations have failed to prioritize SAF over other renewable fuels. For instance, in 2018, the United States produced over 300m gallons of renewable diesel and 32m gallons of ethanol, yet SAF production was limited to just 2m gallons. This trend is seen globally, as renewable fuels for other sectors often receive more substantial incentives and are less expensive to produce (*ICF Report 2021.Pdf*, n.d.).

The shipping industry is another growing consumer of renewable fuels, increasing competition for limited resources. The FuelEU Maritime Regulation, effective January 1, 2025, promotes the adoption of renewable, low-carbon fuels and clean technologies for ships exceeding 5,000 gross tonnage operating in EU ports. This regulation mandates a reduction in emissions from marine fuels, or imposes penalties for non-compliance. Furthermore, the inclusion of shipping in the EU's Emissions Trading System (ETS) starting in 2024 requires vessels to pay for emissions generated on voyages involving EU ports (*EU's Cleaner Marine Fuel Rules Are Inflationary, Shipbrokers Say | Reuters*, n.d.), highlighting the increasing demand for renewable fuels in sectors beyond aviation.

As sectors such as shipping, power generation, and chemicals accelerate decarbonization efforts and EU policies limit certain feedstock options, the competition for renewable resources is expected to intensify. These dynamics underscore the necessity of unified regulatory measures, strategic resource allocation, and targeted incentives to ensure sufficient feedstock availability for SAF. Addressing these challenges is critical to supporting SAF's pivotal role in reducing emissions and advancing sustainability in aviation.

4.3 Supply Chain and Infrastructure Requirements

Coordination with traditional fuel industries is the cornerstone in the development of SAF supply chains since current fuel certifications mandate blending SAF with conventional jet fuel. As SAF production is still an emerging sector, supply chains are currently underdeveloped, vary by region, and will require substantial resources and investment to become fully operational. In order to meet expectations, efforts to expand SAF production will need to focus on advancing R&D and scaling up pilot projects to commercial-scale production. It is also important to conduct demonstration projects to validate optimized supply chain logistics and business models. These initiatives will need rely heavily on public–private partnerships and collaboration with international organizations, certifications and local stakeholders to address logistical challenges and create a robust, scalable SAF supply chain.

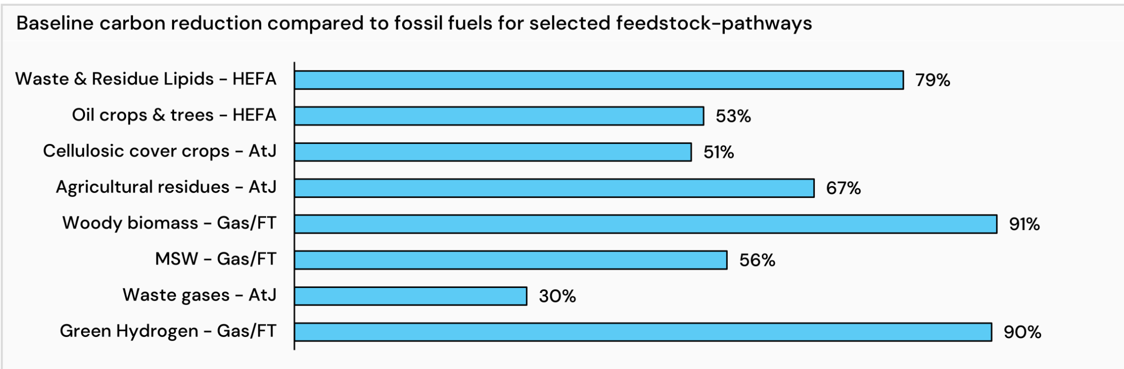
Policies and regulatory frameworks will need to be explored and stress the implementation of strategies to boost SAF availability. Gaps between existing frameworks will need to be addressed, as well as evaluate of the potential impact of new policies on the quality and accessibility of SAF to drive industry growth effectively. This should include initiatives to improve infrastructure, such as upgrading existing fuel storage and distribution systems to accommodate SAF blends and constructing dedicated SAF production facilities in strategic locations. Investment in pipeline networks and logistical hubs could further streamline the supply chain, reducing costs and ensuring consistent fuel availability.

4.4 Environmental Impact

The environmental impact of SAF encompasses a range of factors that extend beyond its potential to reduce GHG emissions. This includes considerations of air quality improvements, resource sustainability, and land use changes associated with its production and use.

The carbon reduction values compared to fossil fuels, as shown in the below Figure, demonstrate significant variation depending on the feedstocks and production pathways used, including ILUC. Generally, fuels derived from feedstocks with minimal ILUC impact, such as waste and residue lipids, achieve higher carbon reductions. Conversely, feedstocks cultivated on dedicated land, such as oil crops, trees, and cellulosic cover crops, tend to result in lower carbon reductions due to their greater ILUC impact (*ICF Report 2021.Pdf*, n.d.).

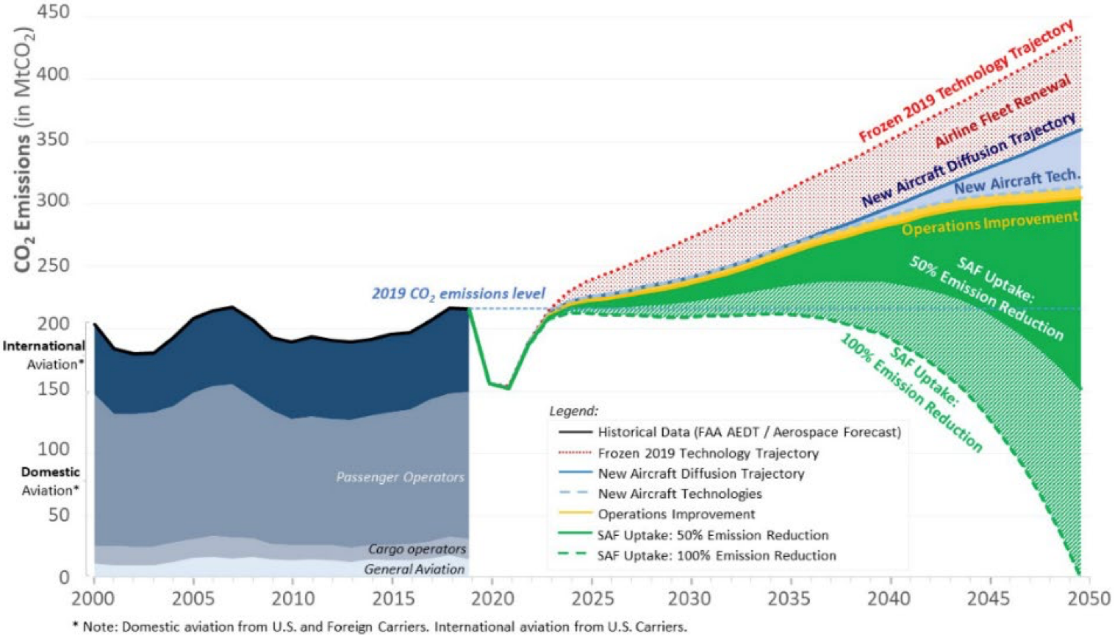
Figure 10: Baseline Carbon Reduction in Comparison du Fossil Fuels



(*ICF Report 2021.Pdf*, n.d.)

The above graph showcases baseline carbon reductions for selected SAF feedstock-pathways compared to fossil fuels, offering a comparative view of their environmental performance. While high-performing pathways such as woody biomass and green hydrogen show promise, their deployment may face limitations due to feedstock availability and infrastructure-related challenges when considering their scalability. A more detailed graph can be found in Appendix 5.

Figure 11: Projected Aviation CO_2 Emissions Reduction



(*SAF Grand Challenge Roadmap*, n.d.)

The above graph illustrates the trends in CO_2 emissions from aviation between 2000 and 2050, emphasizing the potential impact of SAF and technological advancements on reducing emissions. In contrast to the on-road transportation sector, energy alternatives such as electricity and hydrogen are unlikely to be feasible options for commercial aviation in the short to medium term. The industry is expected to depend on high-energy-density liquid fuels for the foreseeable future.

Under the "Frozen 2019 Technology Trajectory," which assumes no further technological advancements or operational improvements beyond 2019 levels, emissions are projected to rise sharply due to increasing air traffic demand, reaching unsustainable levels by 2050. However, scenarios involving technological and operational improvements present a more optimistic outlook. Fleet renewal and the diffusion of new aircraft technologies lead to moderate reductions in emissions, as more efficient and modern aircraft replace older models. Further advancements, such as new aircraft technologies and improvements in operations, including optimized flight paths and fuel efficiency measures, demonstrate a greater potential for reducing emissions.

The role of SAF is particularly prominent in the graph, with two scenarios depicting its impact. A 50% reduction in emissions through SAF uptake results in substantial mitigation, though emissions remain above the 2019 baseline by 2050. Conversely, a 100% SAF uptake scenario shows a dramatic decline in emissions, potentially achieving net-zero CO_2 emissions by 2050. These reductions highlight the critical need for scaling up SAF production and adoption, as well as overcoming challenges related to feedstock availability and infrastructure development.

Even though SAF is necessary to decarbonize the industry, different feedstocks and production processes used for SAF result in varying levels of CO_2 emissions reductions. These differences are influenced by factors such as feedstock type, production pathway, and lifecycle impacts, including DLUC and ILUC, as well as energy inputs as seen earlier in this paper. A detailed comparison of the CO_2 emission outcomes for various feedstocks and processes is provided in Appendix 6.

4.5 Key Takeaways on SAF's Future Potential

This chapter highlights the significant challenges and opportunities in meeting the aviation sector's growing demand for sustainable solutions. While SAF shows promise in reducing GHG emissions, its current production capacity is far from sufficient to meet future needs. The rapid growth in passenger and freight traffic, particularly in emerging economies, emphasizes the urgency of scaling up SAF production.

However, SAF’s reliance on limited feedstocks, such as waste fats and oils, limits its scalability. Diversifying production methods and increasing research into alternative pathways will be essential to overcoming these constraints. Additionally, ensuring sustainability across the SAF supply chain is critical, as variations in feedstock and production processes can impact environmental benefits. Robust certification systems and transparent monitoring will play a key role in maintaining sustainability standards.

The competition for renewable feedstocks across industries further complicates SAF’s adoption. Sectors such as shipping and road transport are also vying for these resources, underscoring the need for targeted policies and incentives to prioritize SAF production for aviation. Infrastructure challenges, including the blending requirements with traditional jet fuel, add another layer of complexity that requires collaboration across stakeholders.

5. Economic Analysis

Economic factors play a crucial role in the development and adoption of SAF. This section explores the costs, market dynamics, and overall economic viability of SAF, including a comparison with fossil fuels. By analyzing production expenses and industry trends, this section aims to highlight the financial challenges and opportunities associated with SAF, offering a clearer understanding of its potential.

5.1 Cost of SAF Production

Analyzing the key cost drivers of SAF production is crucial for understanding how SAF is priced, including comparisons to conventional jet fuels and factors affecting economic viability. These drivers include feedstock availability, the efficiency of production pathways, and the energy requirements for converting raw materials into fuel. Furthermore, the costs of various SAF production technologies, such as HEFA, ATJ, and FT, are evaluated, emphasizing their cost structures and scalability limitations. This analysis provides a comprehensive view of the financial challenges associated with SAF adoption and highlights strategies to bridge the cost gap with conventional jet fuel.

5.1.1 Feedstock Prices

The first cost driver for SAF is feedstock. Their availability is crucial when evaluating the potential costs associated with processing. Appendix 6 highlights the potential biomass feedstock in MT/year. Fuels derived from second-generation and third-generation feedstocks are collectively known as Advanced Biofuels and they are anticipated to dominate the supply of SAF for aviation over the next 10 to 15 years. This is largely due to regulatory restrictions that prohibit the production of SAF from food crops. The focus on utilizing waste fuels stems from repurposing surplus materials produced through existing processes or cycles, as these materials avoid the use of additional resources, such as land for agriculture, water, fertilizers, or land clearing, promoting a more sustainable production model.

Second-generation feedstocks are typically the most expensive of the four categories due to their association with industrial processes, which results in a limited and constrained supply, and difficult to predict and project. On the other hand, third-generation feedstocks are widely available in nature, making them less costly than the restricted supply of the second-generation feedstocks. However, their supply chains are still in the early stages of development. Additionally, these feedstocks have the highest potential for environmental benefits compared to the other generations, as they are made up of waste materials and by-products that would otherwise need to be discarded, potentially contributing to further emissions. The below Table highlights the production potential relative to the biomass:

Table 3: Biomass Feedstock Potential per Year

Feedstock	Potential (million dry tons/year)
Biomass based on 2021 ethanol and biodiesel production capacity [a]	
Seed oils	9
Corn grain	148
Biomass based on *2016 Billion-Ton Report* [b]	
Forestry resources and woody wastes	133
Woody energy crops	71
MSW	55
Agricultural residues	176
Herbaceous energy crops	340
Algae input based on 2017 *Algae Harmonization Study* [c]	
Algae	235
Biomass based on 2017 *Biofuels and Bioproducts from Wet and Gaseous Wastes* [d]	
Fats, oils, and greases (FOG)	7
Wet wastes (animal waste, food waste, wastewater solids)	78
TOTAL	**1,252**

[a] Feedstock input based on existing production capacity divided by yield. 2019 biodiesel production capacity of 2.54 billion gal/yr[18] with assumed biodiesel yield of 281 gallons of gasoline equivalent per ton seed oil. Ethanol production capacity of 17.44 billion gal/yr[19] with yield of 118 gal ethanol/dry ton.

[b] Feedstock inputs are from the *2016 Billion-Ton Report*.[20] All pathways assume reference case 2040 projections at $60/ton.

[c] Algae feedstock is based on 2017 *Algae Harmonization Study*.[21] Total 235 million tons/yr based on the cumulative volume from the saline scenario, Table 11.

[d] Wet waste volume is from *Biofuels and Bioproducts from Wet and Gaseous Waste Streams*[22]; includes wastewater residuals, animal wastes, and food waste from Table 2-1. Total volume is scaled up by 9% for assumed population growth between 2017 and 2030.

(*SAF Grand Challenge Roadmap*, n.d.)

The table underscores the earlier point regarding the varying cost and availability of feedstocks, particularly for second-generation and third-generation categories. Second-generation feedstocks, such as FOG, and agricultural residues, demonstrate relatively constrained supply. For instance, FOG availability is limited to 7m dry tons per year, highlighting the challenges posed by its restricted supply. On the other hand, agricultural residues show a higher potential of 176m dry tons annually, although they are still constrained compared to more abundant options like herbaceous energy crops.

Third-generation feedstocks, such as algae (23m dry tons) and wet wastes (78m dry tons), clearly exhibit their abundant nature. Algae offers significant scalability due to its vast availability, aligning with the assertion that third-generation feedstocks benefit from lower associated costs. Moreover, these feedstocks represent by-products or waste streams, which would otherwise require disposal and potentially generate emissions. This aligns with their environmental advantages relative to second-generation feedstocks.

To put the above into perspective, the below table made available by ICAO provides valuable insights regarding current capacity and production. However, the most important values in this case will be the yield and feedstock price[6].

Table 4: Feedstock Information

Processing Technology	Feedstock	Yield (ton distillate/ton feedstock)	Feedstock Price	Total Capacity (million L/year)		SAF production (million L/year)	
				nth	pioneer	nth	pioneer
FT*	MSW	0.31	$30/ton	500	100	200	40
FT*	forest residues	0.18	$125/ton	400	100	160	40
FT*	agricultural residues	0.14	$110/ton	300	100	120	40
ATJ	ethanol	0.6	$0.41/L	1000	100	700	70
ATJ	isobutanol-low	0.75	$0.89/L	1000	100	700	70
ATJ	isobutanol-high	0.75	$1.20/L	1000	100	700	70
HEFA	FOGs	0.83	$580/ton	1000	-	550	-
HEFA	soybean oil***	0.83	$809/ton	1000	-	550	-
FT	CO2 from Direct Air Capture (DAC) , H2	0.24	$300/t, $6/kg	1000	-	200	-
FT	waste CO2, H2	0.24	$300/t, $6/kg	1000	-	200	-
Pyrolysis**	forest residues	0.23	$125/ton	400	100	180	40
Pyrolysis**	agricultural residues	0.21	$110/ton	400	100	180	40

*feedstock price is for pre-processed feedstock
**pyrolysis ASTM approval is pending.
***2013-2019 average price of soybean and canola oils,

(*SAF Rules of Thumb*, n.d.)

One notable observation is the variation in yield efficiencies across different processing technologies. For instance, the HEFA technology demonstrates the highest yield at 0.83 tons of distillate per ton of feedstock, which underscores its current dominance in SAF production. However, the feedstocks associated with HEFA, such as FOG and soybean oil, are expensive¾priced at USD 580 and USD 809 (current price of soybean oil in Jan 25 lays around USD 1,140 per MT) respectively per ton. This reliance on high-cost feedstocks poses a significant economic challenge, particularly as SAF production scales up to meet rising demand.

Conversely, the FT technology offers the advantage of utilizing lower-cost feedstocks such as MSW and forest residues, priced at USD 30 and USD 125 per ton for the latter. Despite this cost advantage,

[6] Disclaimer: as feedstock prices are constantly evolving, we will base our analysis and draw our conclusions using the numbers provided by ICAO and our own assumptions.

the yields for FT technology are lower, ranging from 0.14 to 0.31 tons of distillate per ton of feedstock. This trade-off highlights the need for further technological advancements to improve conversion efficiencies while maintaining cost advantages.

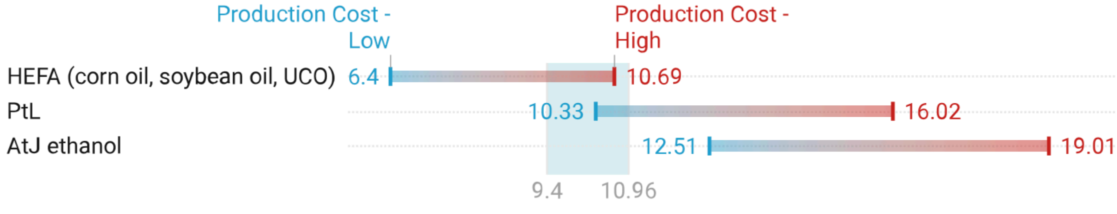
When it comes to the ATJ pathway, the process provides intermediate yields of 0.6 to 0.75 tons of distillate per ton of feedstock. However, the feedstock prices for ATJ vary significantly, with ethanol priced at USD 0.41 per liter and isobutanol ranging from USD 0.89 to USD 1.20 per liter.

Finally, the inclusion of Direct Air Capture (DAC) with CO_2 and hydrogen feedstocks in the FT pathway represents a cutting-edge approach to SAF production. With yields of 0.24 tons of distillate per ton of feedstock and feedstock prices of USD 300 per ton or USD 6 per kg for hydrogen, this method holds promise for long-term scalability. However, its high costs highlight the need for significant investment in renewable energy and infrastructure to make this pathway viable on a commercial scale.

5.1.2 Production Costs

Considering the findings from the previous section, attention now turns to the costs associated with SAF production. As per RMI, these costs, ranging from USD 6.40 to USD 19.01 per gallon, present a green premium[7] that positions SAF as a competitive alternative to fossil-based jet fuel under various conditions. Specifically, the HEFA pathway having relatively lower production costs between USD 6.40 and USD 10.69 per gallon, offers a range of viable and bankable project opportunities even in the current market landscape. This creates promising potential for both SAF producers and investors seeking to enter or expand in this sector (Azarova et al., 2024).

Figure 12: Current SAF Production Costs

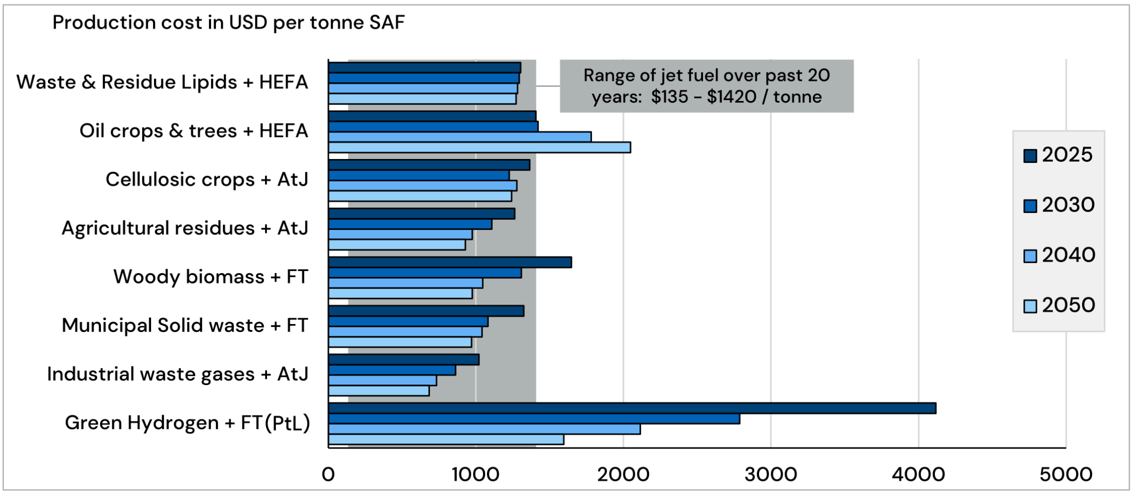


(Azarova et al., 2024)

[7] Green premium: the additional cost of opting for a sustainable option over the conventional alternative.

PTL[8]'s elevated costs are primarily driven by the reliance on renewable electricity and green hydrogen, both of which are costly to produce at scale. The production process involves advanced technologies such as direct air capture and hydrogen synthesis, further adding to operational expenses. In contrast, ATJ ethanol has the highest production costs among the SAF pathways, with a range of USD 12.51 to USD 19.01 per gallon. These costs are attributed to the energy-intensive conversion process, and the relatively lower technological maturity of ATJ compared to other pathways. Future outlooks, however, are optimistic, as can be seen in the below Figure:

Figure 13: Outlook on Future Production Costs as Technologies Evolve



(*ICF Report 2021.Pdf*, n.d.)

The graph highlights the projected production costs for various SAF pathways from 2025 to 2050, compared to the historical price range of fossil-based jet fuel (USD 135 to USD 1,420 per MT). HEFA pathways, particularly those using waste and residue lipids, are as mainly projected, among the most cost-competitive, with costs declining to align with conventional jet fuel by 2050. The overall trend suggests declining SAF costs over time, driven by technological advancements and policy support.

5.2 Market Dynamics

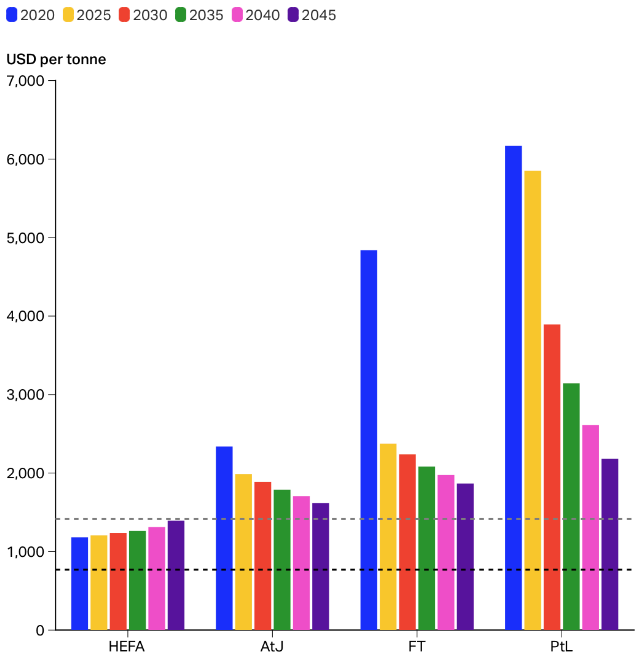
Currently, the cost of SAF is primarily influenced by production expenses. With rising demand and constrained supply, the market is still in its early stages of development. In 2022, the estimated average cost of SAF was approximately USD 2,400 per MT, with notable differences observed across

[8] Power-to-Liquid: aka as Fischer-Tropsch process.

various regions. This price was roughly two and a half times higher than that of conventional jet fuel (IATA, 2023, n.d.).

IATA and S&P has provided a projected minimum selling price for SAF in the coming years, excluding additional market costs such as market premiums, logistics, certifications, transaction costs, and supply chain markups. These additional costs can differ substantially. In 2024, the gap between production expenses and market pricing for HEFA SAF in Europe climbed to approximately USD 1,000 per MT (*SAF Procurement*, 2024).

Figure 14: IATA Analysis of SAF Market Trends (USD/MT)



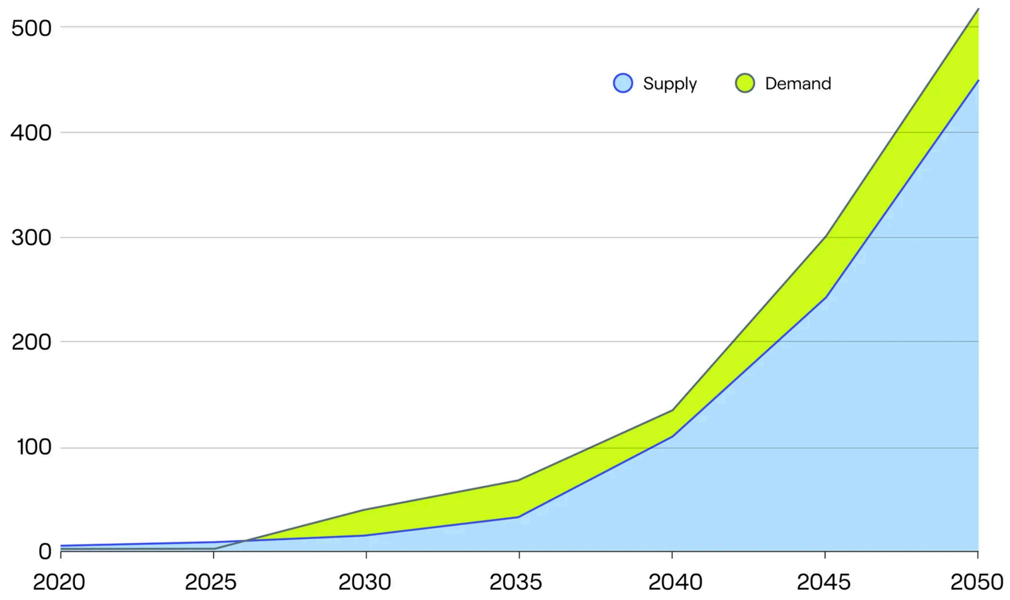
(*SAF Procurement*, 2024)

The graph above illustrates that the cost of the HEFA method is forecasted to go through a slight increase in comparison to other production pathways. This could be explained by the limited availability of feedstocks such as FOG, which HEFA heavily relies on, creating supply constraints and can therefore drive-up prices. Growing competition from other industries, such as road transportation and bio-based materials, will further add to the demand.

5.3 Demand for SAF

With the continuous evolution of the aviation industry, there is a clear forecast of surge in demand for SAF in the coming years. The projected demand vs supply for SAF can be found in the Figure below, which helps explain the gradual increase in HEFA SAF prices as seen above, given its status as the most widely commercialized option available.

Figure 15: Demand vs Supply of SAF



(*SAF | Outlook for Sustainable Aviation Fuel*, n.d.)

Post-2030, the demand for SAF is expected to grow exponentially, driven by a convergence of factors that position SAF as a pillar of aviation's decarbonization efforts. This sharp increase reflects the anticipated scaling of SAF adoption as technological innovations improve production processes, reduce costs, and enhance the overall feasibility of large-scale deployment. We can also observe that the demand is projected to surpass supply as of 2026.

However, unlike conventional demand, which is driven primarily by natural market forces like consumer behavior and cost competitiveness, SAF demand is heavily influenced by regulatory mandates, corporate ESG commitments, and international agreements like ICAO's CORSIA or the European Union's ReFuelEU Aviation. While the demand projections highlight the growing role SAF will play in aviation, they also underscore its dependence on sustained political will and policy enforcement. Shifts in government priorities, particularly in countries where climate skepticism is prevalent, could disrupt this trajectory. For instance, changes in leadership or economic pressures could lead to reduced subsidies, delays in infrastructure investments, or weakened mandates, all of which could threaten the scale-up of SAF production.

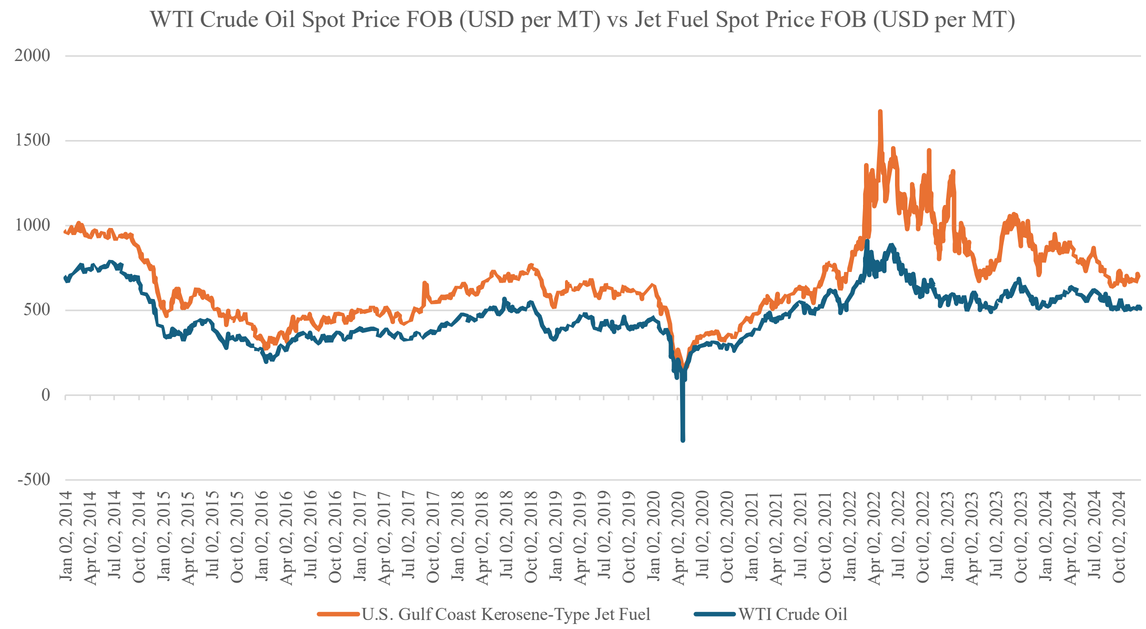
To drive demand for SAF, several key actions are needed., including the aforementioned mandates which require fuel providers to include a set percentage of SAF in their supply. Additionally, updating biofuel policies to support SAF and integrating it into existing transport policies can also boost its use. Financial incentives are essential to make SAF more economically viable. Lastly, collaboration between international organizations and stakeholders is crucial to coordinate efforts.

5.4 Comparative Cost Analysis

Understanding the economic landscape of aviation fuel is essential for evaluating the viability of SAF as a long-term solution. Comparing conventional jet fuel prices with current and projected SAF costs highlights the financial differences and challenges that need to be addressed to achieve widespread SAF adoption. This analysis not only sheds light on the price gap but also explores the factors driving these differences, such as production technologies, feedstock availability, and market demand.

The below Figure compares the WTI crude oil prices and jet fuel spot prices with data collected from Thomson Reuters, with both datasets converted to MT for consistency purposes:

Figure 16: Historical WTI Crude Oil Prices vs Jet Fuel Spot Prices



During periods of crude oil price increases, jet fuel prices often rise at a steeper rate because of the added costs in refining, transportation, and market demand for jet fuel. For instance, the spike around 2021–2022 suggests that jet fuel prices were disproportionately higher than crude oil prices, reflecting supply chain disruptions of crude oil with the Russo-Ukrainian war, compiled with the increased aviation demand post-pandemic. The sharp increase in crude oil prices, driven by supply disruptions and market instability caused by the war, underscored the aviation sector's reliance on volatile fossil fuel markets. The rising prices of conventional jet fuel during this period created a temporary economic incentive for SAF adoption. As the gap between fossil-based jet fuel prices and SAF narrowed, airlines and policymakers could perceive SAF as a more viable option, even with its current green premium.

From a comparative perspective, SAF's pricing currently exceeds the typical range of jet fuel. However, SAF's price volatility is expected decrease over time, since it depends on renewable feedstocks and localized production rather than the global oil market. This creates an economic argument for SAF adoption, as it has the potential to offer greater long-term pricing stability compared to conventional jet fuel, particularly as production scales and technological advancements are expected to reduce costs. Additionally, since current blending regulations allow SAF to constitute up to 50% of the final fuel mix with conventional kerosene, it can help mitigate price volatility for the end product used by airlines. By incorporating SAF into the fuel supply, airlines can achieve a more balanced cost structure that is less dependent on the fluctuations of crude oil and jet fuel markets, providing economic and operational benefits alongside environmental advantages.

5.5 Cost to Airlines, Passengers and Air Cargo

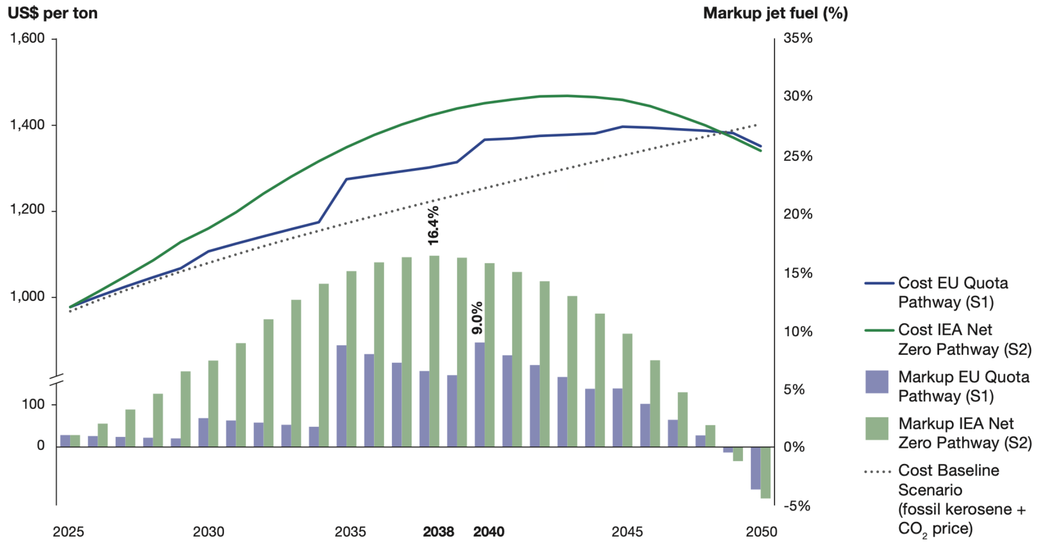
The rising focus on sustainability in aviation brings questions about how these advancements will influence consumers. As SAF becomes a larger part of the aviation fuel blend, understanding its impact on costs passed down to passengers is becoming increasingly important. This section delves into the broader context of how the transition to more sustainable fuels may shape the financial experience for travelers, reflecting the intersection of environmental progress and economic realities.

According to official reports from IATA, the airline industry generated an average net profit of USD 6.40 per departing passenger in 2024 and is expected to reach a net profit of USD 7.00 per passenger in 2025 (*IATA Global Outlook 2024.Pdf*, n.d.). By taking into consideration previously covered elements, it would suggest that the estimated global net profit of the aviation industry in 2024 amounted to a total of USD 64bn.

Fossil-based jet fuel remains the largest expense for airlines, accounting for around 30% of global industry costs in 2024 (*IATA Global Outlook 2024.Pdf*, n.d.). Transitioning to SAF could have significant implications for passengers. As SAF adoption increases, it is crucial to assess how this shift might influence ticket prices and overall affordability. By understanding the potential cost impact on travelers, the industry can better navigate the balance between sustainability efforts and maintaining accessible air travel for consumers.

When following the IEA Net Zero Pathway, the maximum price increase is reached in 2038 at approximately 16%. This peak is driven by the potential increased reliance on PTL fuels, which can become more prevalent depending on their technological readiness and the necessity to meet high SAF demand. After 2040, the cost of jet fuel, including the assumed SAF share in each scenario, is projected to decrease due to two main factors. Firstly, the cost of PTL is expected to decline significantly. Secondly, CO_2 prices are anticipated to rise steadily, as they are considered a key mechanism for driving GHG reductions and are already implemented in several countries worldwide. Higher CO_2 prices can substantially increase the cost of fossil kerosene, thereby narrowing the price gap with SAF (*PwC & Strategy&, 2022*, n.d.). The Figure below shows the elements discussed above:

Figure 17: Price Increase for Different IEA Scenarios

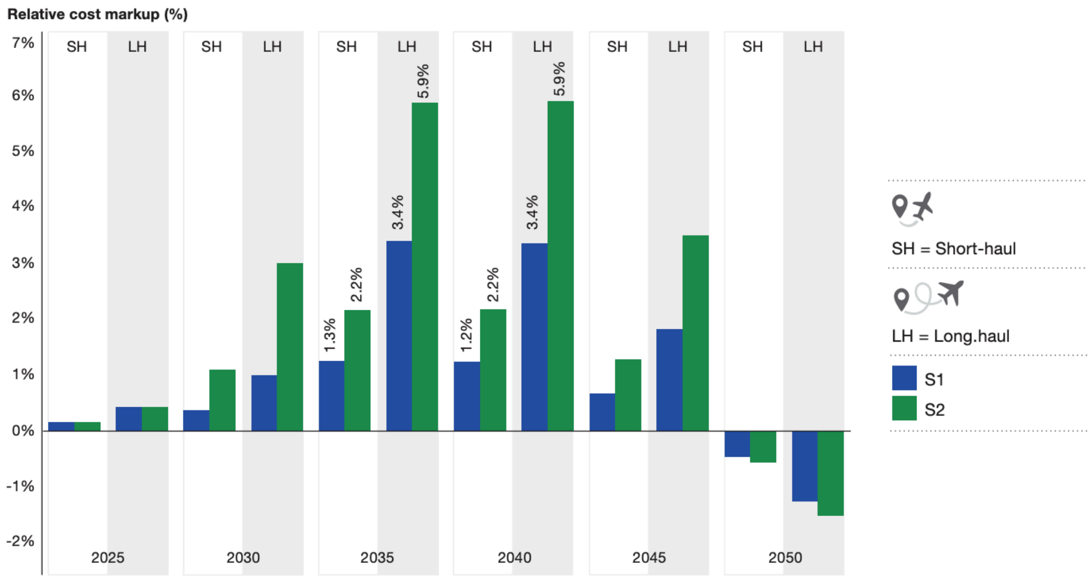


(*PwC & Strategy&, 2022*, n.d.)

The price increase can however impact short-, medium-, and long-haul routes differently. Long-haul flights are expected to experience a greater relative price increase compared to short-haul flights, primarily due to fuel costs as they make up a larger proportion of total operational expenses for long-haul flights (*PwC & Strategy&, 2022*, n.d.). Consequently, the relative cost increase per flight for these routes is more than double that of short-haul routes under Scenario 1[9], as can be seen below:

[9] S1: based on the minimum required SAF blending ratios of the 2021 ReFuelEU Aviation directive

Figure 18: Estimated Relative Cost Increase in Flights



(*PwC & Strategy&, 2022*, n.d.)

To put the above into another perspective, fuel costs for low-cost carriers represent a much larger proportion of total operational expenses compared to full-service network carriers. This means that when SAF costs rise, low-cost carriers experience a higher relative increase in their overall costs, which could significantly reduce their profitability. However, in absolute terms, the additional SAF costs for low-cost carriers are smaller than those for full-service network carriers as full-service carriers typically operate with higher baseline costs. On average, the total SAF cost increase for a low-cost carrier is expected to be only half of that for a full-service carrier as they have an advantage in cost distribution. Low-cost carriers generally operate with higher passenger capacity and load factors and as a result, the additional SAF costs are spread across a larger number of passengers, leading to a lower cost increase per passenger compared to full-service network carriers (*PwC & Strategy&, 2022*, n.d.).

Over a ten-year period (2025–2035), the total additional SAF costs are projected to differ significantly between the two types of carriers. Full-service network carriers are expected to face total additional costs of USD 3bn under Scenario 1 or USD 8bn under Scenario 2[10], while low-cost carriers face much smaller total additional costs of USD 225m under Scenario 1 or USD 610m under Scenario 2 (*PwC & Strategy&, 2022*, n.d.).

[10] S2: based on the SAF blending ratios required to achieve the IEA Net Zero Pathway by 2050

Ticket prices are expected to rise variably depending on travel class and flight distance, reflecting passengers' willingness to pay and the higher fuel expenses tied to long-haul flights. For instance, non-economy passengers could see price increases of up to USD 36.30 for short-haul flights and USD 62.70 for long-haul flights under IEA's Scenario 2. Economy-class travelers may experience smaller adjustments, such as USD 2.00 for short-haul and USD 17.00 for long-haul routes (*PwC & Strategy&, 2022*, n.d.). These differences underscore how SAF-related costs are unevenly distributed across passenger segments and flight types, with longer routes and premium travel bearing a larger share of the financial burden.

The adoption of SAF in aviation is expected to impact ticket prices, with costs varying based on flight type and carrier. Long-haul flights and full-service carriers face higher relative price increases due to greater fuel demands, while low-cost carriers benefit from distributing costs across more passengers. Over time, SAF costs are projected to decrease, narrowing the price gap with traditional jet fuel and balancing affordability with sustainability goals.

When it comes to air cargo transportation, PwC estimates that the cost per kilogram of transported goods will rise from USD 6.60 per kg to USD 7.60 per kg, reflecting a 15.1% increase in the case of a 100% SAF use (PwC & Strategy&, 2022, n.d.).

5.6 Key Stakeholders

The successful adoption and expansion of SAF rely on a diverse group of stakeholders, each playing a critical role in addressing the economic and logistical challenges involved. Governments and regulatory frameworks, such as the EU's ReFuelEU Aviation and the U.S. Inflation Reduction Act, provide vital financial incentives and blending mandates to bridge the cost gap between SAF and conventional jet fuel. These policies must also address the competition for feedstocks with other industries, ensuring a sustainable and sufficient supply for SAF production.

Banks and financial institutions are increasingly integrating sustainability into their financing strategies, offering preferential terms for SAF projects based on feedstock type and production processes. These "sustainable discounts" could incentivize producers and traders to prioritize greener practices while reducing borrowing costs. Investors are also pivotal in funding SAF infrastructure and technological advancements, with growing interest in renewable energy and decarbonization projects.

Airlines are essential demand drivers, navigating the operational cost increases associated with SAF adoption, whilst consumers are becoming increasingly aware of environmental issues and therefore influence demand. However, they remain sensitive to ticket price increases, which could limit SAF adoption without adequate support.

NGOs and industry bodies like IATA and ICAO play a critical role in fostering global cooperation, ensuring compliance with sustainability standards, and promoting transparency. By aligning the efforts of stakeholders, these organizations help address the economic and environmental challenges of SAF, paving the way for a sustainable transition in aviation.

5.7 Key Takeaways

The adoption of SAF presents both significant opportunities and challenges for the aviation industry. While the technology is promising, its high costs and reliance on limited feedstocks pose major barriers to widespread implementation. Addressing these issues will require strong collaboration between governments, airlines, and producers, alongside sustained investments in research, infrastructure, and policy incentives.

Government support is particularly crucial to bridge the cost gap and ensure long-term regulatory stability. At the same time, airlines must balance sustainability goals with the need to keep air travel affordable for passengers. Clear communication about the environmental benefits of SAF will be essential to build public acceptance for potential price increases.

SAF has the potential to transform aviation into a more sustainable industry, but this transition depends on bold and coordinated actions. Without strong and consistent efforts, the industry risks falling short of its climate targets, leaving SAF an underutilized solution rather than a driving force for decarbonization.

6. Regulatory and Policy Challenges

Scaling the production and use of SAF faces several challenges, mainly due to inconsistent and fragmented regulations across different regions. While initiatives like the EU's ReFuelEU Aviation Regulation and the U.S. SAF Grand Challenge provide goals and financial incentives, the lack of global coordination makes it harder for stakeholders to meet varying requirements. This patchwork of policies slows down SAF adoption and creates barriers to establishing a unified market for sustainable aviation fuels.

Political and geopolitical factors also play a critical role in shaping SAF development. Changes in leadership, shifting priorities, or policy reversals can disrupt progress and reduce financial support for SAF projects. For instance, the expiration of key tax credits in the U.S. and potential political changes may undermine incentives needed to scale production. Additionally, geopolitical tensions, such as trade disputes or conflicts, can disrupt feedstock supply chains and limit international collaboration.

These challenges highlight the importance of aligning regulations, ensuring long-term policy stability, and building resilience to political and geopolitical uncertainties. Tackling issues like feedstock availability, financial support, and global cooperation will be essential for expanding SAF production and meeting the aviation sector's sustainability goals. Without coordinated efforts, achieving large-scale SAF adoption may face significant delays.

6.1 Political Shifts and Climate Actions

6.1.1 The United States

The rise of right-wing movements in the United States and globally is creating additional challenges for climate policies and the shift to renewable energy. In the United States, the election of Donald Trump, a known skeptic of climate change, has raised concerns about the country's commitment to sustainability efforts. Under Trump's first term as president, he announced the withdrawal of the United States from all participation in the 2015 Paris Agreement on climate change, which was later reversed by his successor Joe Biden. Many now expect Donald Trump to again withdraw the United States from the Paris Climate Agreement, which could delay international efforts to reduce the global greenhouse emissions. He has also voiced support for expanding domestic oil and gas production and

overturning the Inflation Reduction Act, a key green energy initiative introduced by the former president Joe Biden. (*Will the US Withdraw from the Paris Agreement?*, n.d.).
Additionally, the SAF blenders tax credit and Clean Fuel Production Credit under the IRA are set to expire at the end of 2024 and 2027, respectively. As Donald Trump is elected for the next presidency, these credits may not be immediately eliminated but could face challenges in being renewed, posing a significant threat to SAF production and adoption.

The climate change skepticism also extends beyond Trump. Many Republican lawmakers oppose environmental policies, as highlighted in a 2023 report revealing that 37 states introduced 165 anti-ESG laws since 2021, often driven by fossil fuel interests. These efforts aim to counter corporate actions focused on environmental, social, and governance (ESG) criteria, which some conservatives label "woke capitalism." Additionally, some Republican-led states have restricted public pension funds from investing in ESG-focused portfolios (*2023 Anti-ESG Statehouse Report Right-Wing Attacks on the Freedom to Invest Responsibly Falter in the States 1.Pdf*, n.d.).

The financial sector is also a target for conservative political pressure. Republican politicians and right-wing groups have accused investment firms of practicing "woke capitalism". As a response, many of US biggest investment firms, like BlackRock and State Street, as well as companies in which they invest, are pulling away from ESG fund offerings. Also, at least 20 states have implemented local laws to forbid public pension funds under their control from investing in ESG funds.(*How BlackRock Abandoned Social And Environmental Engagement*, n.d.).

6.1.2 Global Movements

Globally, right-wing populist parties are slowing climate progress. European leaders like Marine Le Pen in France and Giorgia Meloni in Italy have opposed key EU climate measures, citing economic concerns. Research shows that stronger right-wing representation often leads to weaker climate policies, although EU membership and having a proportional representation voting system can limit this impact. Studies also reveal that some right-wing parties see EU climate initiatives as elitist and out of touch with ordinary citizens (Lockwood & Lockwood, 2022).

Economic difficulties further hinder the transition to greener energy. Rising inflation, security concerns, and the costs of environmental measures, such as switching to electric vehicles, have shifted public attention away from climate action. In the 2024 EU elections, Green parties experienced significant losses, reflecting voter dissatisfaction with the economic strain of environmental policies (*Green Parties Suffer EU Poll Drubbing*, 2024).

Globally, fossil fuels still dominate the energy mix, accounting for 80% of energy use (Ernström, n.d.). Transitioning to renewables requires both lifestyle and business model changes, particularly for industries reliant on fossil fuels. This reliance helps explain the persistence of climate change denial, which is often tied to right-wing nationalism and fossil fuel lobbying.

The rise of right-wing movements reflects a growing conflict between economic concerns and environmental goals. These movements often portray climate policies as costly or disconnected from everyday challenges, especially in regions facing inflation and energy security issues. This resistance complicates the shift away from fossil fuels, highlighting the difficulty of balancing short-term economic needs with long-term sustainability. Fossil fuel dominance and corporate advocacy further add to the challenge, showing the need for policies that address both public skepticism and economic inequalities to drive effective climate action.

6.2 The Role of International Organizations

International organizations play a pivotal role in advancing the adoption and scalability of SAF by establishing global standards, fostering collaboration among stakeholders, and promoting sustainable practices in the aviation sector. Agencies such as ICAO and IATA have been at the forefront of these efforts, addressing the complex challenges associated with SAF production, distribution, and adoption.

The ICAO, through initiatives such as CORSIA, has set an ambitious framework for reducing aviation emissions, encouraging airlines to adopt SAF as a key strategy for meeting carbon-neutral growth targets. The organization also convenes global conferences, like the Third Conference on Aviation Alternative Fuels (CAAF/3), to create comprehensive frameworks for scaling SAF production across diverse geographies. These efforts aim to align stakeholders on lifecycle emissions criteria and sustainability benchmarks, providing a cohesive roadmap for the global aviation sector.

IATA complements these efforts by advocating for policy harmonization and providing technical guidance to airlines and fuel producers. The association actively works with governments and industry players to establish financial incentives and regulatory support for SAF, highlighting its economic viability and environmental benefits. IATA's role in fostering public-private partnerships has been instrumental in driving investment into SAF research and development, as well as infrastructure upgrades.

Beyond aviation-specific organizations, entities such as the United Nations Framework Convention on Climate Change (UNFCCC) and the World Bank contribute by addressing broader sustainability issues and providing funding mechanisms. These organizations facilitate cross-sectoral collaboration, enabling the aviation sector to leverage best practices and innovations from other industries, such as renewable energy and sustainable agriculture.

In summary, international organizations serve as catalysts for the widespread adoption of SAF by promoting cohesive policies, offering financial and technical support, and uniting global stakeholders under a shared vision for a sustainable aviation future. Their continued leadership is essential for overcoming economic, regulatory, and technical barriers to SAF implementation.

6.3 Key Takeaways

The fragmented regulations and political instability surrounding SAF present significant challenges to its large-scale adoption. While initiatives like the EU's ReFuelEU Aviation Regulation and the U.S. SAF Grand Challenge offer valuable frameworks, their lack of global alignment slows progress and creates uncertainty for stakeholders. Without consistent and coordinated policies, the aviation sector risks inefficiency and delays in achieving sustainability goals.

The rise of climate skepticism and shifting political priorities further complicate these efforts. Right-wing movements and economic concerns have led to reduced support for green policies, threatening critical financial incentives for SAF development. These obstacles reflect a short-term focus on economic pressures at the expense of urgent climate action, putting the aviation industry's decarbonization efforts at risk.

However, international organizations like ICAO and IATA play a crucial role in promoting global cooperation and setting standards. Their efforts provide a roadmap for SAF development, but they require stronger political and financial support to succeed.

In conclusion, SAF's potential to transform aviation highly relies on overcoming fragmented policies and political resistance. Unified global action and long-term commitment are essential to ensure the industry can meet its sustainability targets and transition to a cleaner future.

7. Case Study

7.1 Innovating Sustainability: A Case Study of Neste's Leadership in SAF

Neste is a global leader in renewable and circular solutions, renowned for its pioneering approach to sustainability and innovation. Originally founded in Finland in 1948 to secure the country's oil supply, Neste has transformed from a local oil refiner into a global frontrunner in developing sustainable solutions for road transport, aviation, and the polymers and chemicals sectors. With a strong Nordic heritage and a clear vision for the future, Neste collaborates with partners and stakeholders to create solutions that promote a healthier planet for future generations. This unwavering commitment to sustainability and innovation has positioned Neste as a driving force for change in the energy and chemical industries (*Who We Are*, 2025).

The company's evolution reflects its forward-thinking approach to sustainability. In 1996, the company began experimenting with 100% renewable diesel, setting the foundation for its later advancements. During the 2000s, Neste expanded its renewable diesel production capabilities with significant investments in facilities located in Porvoo, Singapore, and Rotterdam. These developments marked a critical shift toward renewable energy solutions. In 2020, the company announced a strategic initiative to transform its Porvoo refinery into a globally recognized hub for renewable and circular solutions. By 2025, the company pledged to support carbon-neutral growth in aviation, reinforcing its leadership in reducing GHG emissions. Neste has set an ambitious target to help its customers lower their GHG emissions by up to 20 million tons annually by 2030 (*Who We Are*, 2025).

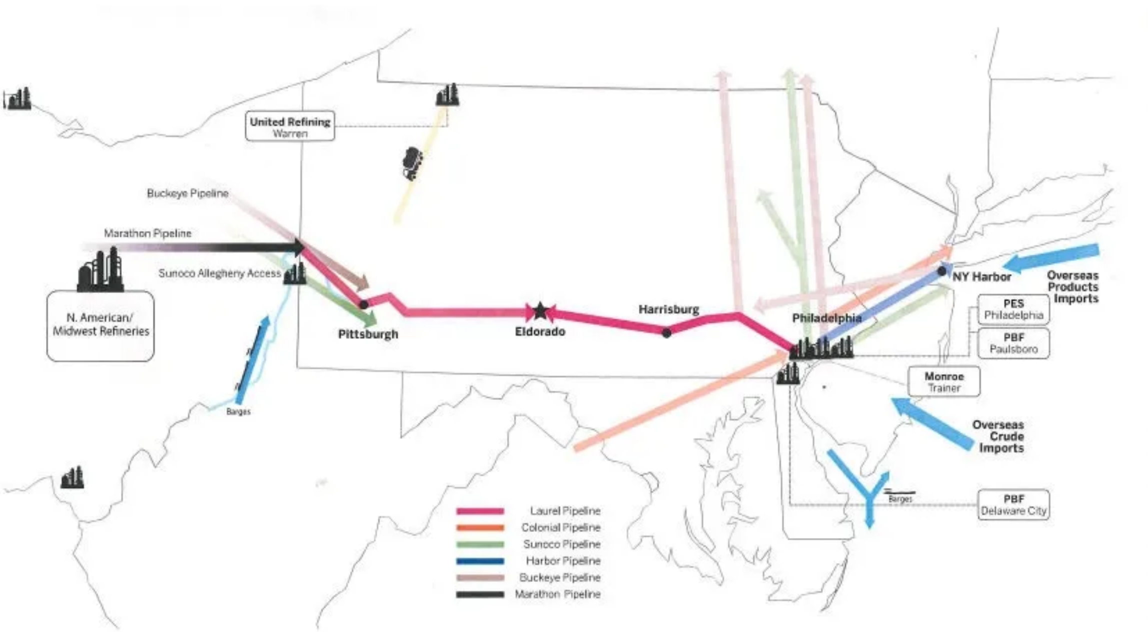
Neste stands as the foremost global producer of SAF, with a history of production and worldwide distribution that dates back to 2011. The company focuses on creating SAF using renewable waste and residues, such as used cooking oil and animal fat waste, sourced sustainably. Neste's impact extends across the globe, with over 70 direct customers actively using Neste MY SAF, and the fuel being directly available at more than 25 key airports (*Neste MY Sustainable Aviation Fuel ™*, 2024).

The involvement of the company does not end there, as they have collaborated with Airbus, a leader in aviation, to embark on a groundbreaking partnership to pave the way for aviation powered entirely by SAF. This collaboration marks a critical step in the industry's transition toward reducing its environmental footprint and achieving carbon neutrality.

A significant milestone in their efforts is the ECLIF project, which sought to assess the broader impacts of operating flights using 100% pure SAF. In 2021, a real-world test flight provided valuable insights, extending beyond CO_2 reduction to examine SAF's influence on contrails and non-CO_2 emissions compared to traditional fossil fuels. Later that year, the partnership achieved another notable accomplishment when an Airbus A380 successfully flew from Nice to Toulouse with one of its four engines powered entirely by SAF. Highlighting SAF's adaptability, the two companies expanded their efforts to rotorcraft. During the Avalon Airshow in 2023, Airbus conducted Australia's first helicopter flight using SAF. These innovative projects underline the transformative potential of SAF across different aviation platforms and underscore Neste and Airbus's commitment to fostering sustainable advancements in the aviation sector (*Neste MY Sustainable Aviation Fuel TM*, 2024).

Neste is also helping to shape the supply chain for SAF by addressing key logistical challenges to support its widespread adoption. In partnership with Delta Air Lines, Neste began working in 2021 on innovative solutions to transport SAF efficiently and at scale. One groundbreaking initiative involved a trial with Colonial Pipeline to test the feasibility of transporting SAF through existing multi-product pipeline systems. During the trial, SAF was successfully delivered over a distance of nearly 1,500 miles (roughly 2414 km), crossing 11 states, from Texas to New York's LaGuardia Airport via the Colonial and Buckeye pipeline networks (*Neste MY Sustainable Aviation Fuel TM*, 2024).

Figure 19: North American Pipeline Networks



(*The Times*, 2018)

This demonstration marked a significant step forward in establishing scalable, cost-effective supply chain solutions for SAF, showcasing how existing infrastructure can be leveraged to accelerate the integration of sustainable fuels into the aviation sector. By tackling such logistical barriers, Neste and its partners are making tangible progress toward reducing aviation's carbon footprint and enabling a greener future for air travel.

This progress in addressing supply chain challenges reflects Neste's commitment to driving innovation and operational efficiency in the SAF market. However, these advancements occur within the broader context of fluctuating financial performance, as the renewable energy sector grapples with volatile market conditions and operational pressures.

Neste's financial performance during the January-September 2024 period reflects both the challenges and opportunities inherent in the renewable energy sector. The company reported a third-quarter EBITDA of EUR 293m, marking a significant 72% decline YoY. This decrease underscores the impact of weakened market conditions, particularly in Renewable Products and Oil Products, where sales margins fell sharply. For Renewable Products, the comparable sales margin dropped from USD 912 per MT in Q3 2023 to USD 341 per MT in Q3 2024, a decline of 62%. These challenges are further intensified by the growing competition in the renewable fuels market, as major players increasingly enter the space, contributing to tighter margins (Tammilehto & Malinen, n.d.).

However, Neste achieved record-high sales volumes of 112k MT of SAF in the third quarter, up from 36k MT a year earlier. This indicates that while margins are under pressure, and competition rises, demand for SAF is growing, driven by regulatory mandates and corporate commitments (Tammilehto & Malinen, n.d.).

7.2 Key takeaways

Neste's leadership in SAF production highlights its commitment to innovation and sustainability, as seen through successful SAF-powered flight trials, strategic partnerships, and efforts to address supply chain challenges. These achievements position the company as a key driver of the aviation industry's transition to greener solutions.

However, Neste faces significant challenges, including declining profit margins and growing competition in the renewable energy market. While record-high SAF sales volumes indicate increasing demand driven by regulations and corporate commitments, the pressure to scale production while managing costs and competition remains substantial.

To maintain its leadership, Neste must continue to innovate, optimize operations, and strengthen partnerships. Its ability to navigate these challenges will determine its role in shaping a more sustainable future for aviation, but success will require overcoming economic pressures and securing resources in an increasingly competitive landscape.

8. Conclusion

The aviation industry is at a pivotal moment in addressing its environmental impact and transitioning toward sustainability. As one of the most significant contributors to global GHG emissions, the sector faces mounting scrutiny and urgent pressure to decarbonize. SAF offers a transformative solution, with the potential to significantly lower lifecycle CO_2 emissions compared to traditional jet fuel. However, its widespread adoption is limited by numerous challenges, including high costs, feedstock availability, fragmented regulatory frameworks, and political resistance.

One of the most critical challenges is the high cost of SAF, which ranges from USD 6.40 to USD 19.01 per gallon depending on the feedstock and production pathway. This significant price gap compared to fossil-based jet fuel creates financial burdens for airlines, potentially leading to ticket price increases, particularly for long-haul flights. Projections suggest ticket prices could rise by up to 16% by 2038 under scenarios requiring extensive SAF use. Although economies of scale and technological advancements are expected to reduce costs over time, achieving economic competitiveness remains a major hurdle. Innovative financing mechanisms, such as green bonds and tax credits, will be essential to bridge the cost gap and incentivize investment in SAF production.

Feedstock availability presents another major limitation. Current SAF production is dominated by HEFA technology, which relies on waste oils and fats that are inherently limited in supply. While second- and third-generation feedstocks, such as municipal solid waste and algae, offer more sustainable alternatives, they require significant infrastructure development and technological advancement to reach full potential. Diversifying production pathways to include technologies like ATJ and FT will be critical for ensuring scalability, but these methods face challenges related to cost, efficiency, and technological maturity. Furthermore, competition for renewable feedstocks from other sectors, such as road transport and shipping, exacerbates the supply constraints, highlighting the need for strategic resource allocation and regulatory prioritization.

Regulatory frameworks have been instrumental in supporting SAF adoption, with initiatives like the EU's ReFuelEU Aviation Regulation and the U.S. Inflation Reduction Act driving progress through blending mandates, tax incentives, and research funding. However, the fragmented nature of global regulations poses significant obstacles. The lack of international coordination results in inefficiencies and creates uncertainty for producers and airlines operating across multiple jurisdictions. A unified global approach is essential to harmonize policies, streamline compliance requirements, and foster a cohesive market for SAF.

Political resistance and climate skepticism further complicate the path to widespread SAF adoption. In the United States, the potential expiration of key SAF tax credits under the Inflation Reduction Act by 2027 illustrates how political instability can disrupt progress. Similarly, rising opposition to climate policies in Europe, driven by economic concerns and public dissatisfaction with the costs of green initiatives, threatens to undermine long-term commitments to sustainability. Right-wing movements in both regions have amplified climate skepticism, portraying environmental policies as economically burdensome or disconnected from immediate public needs. This resistance underscores the need for effective communication and education to build public and political support for SAF and broader decarbonization efforts.

Collaboration among stakeholders is paramount to address these challenges. Governments must provide stable policy environments and sustained financial support to drive investment in SAF production and infrastructure. Financial institutions and investors have a crucial role in funding SAF projects, while airlines must demonstrate leadership by integrating SAF into their fuel mix, despite the associated cost increases. Consumers also play a vital role, as growing awareness of climate change and preferences for sustainable travel options can drive demand for SAF. However, balancing environmental goals with affordability will be key to ensuring public acceptance.

The role of international organizations such as IATA and ICAO cannot be overstated. These entities are essential in leading global cooperation, setting sustainability standards, and promoting best practices across the industry. Their efforts to align stakeholders and address challenges such as feedstock availability, certification systems, and logistical barriers are vital for scaling SAF production and adoption.

Despite the challenges, SAF has a significant opportunity to transform the aviation industry. Beyond reducing emissions, SAF adoption can offer economic benefits such as price stability and enhanced energy security. Its potential to decarbonize aviation, while supporting the industry's growth in a more environmentally responsible manner, makes it a cornerstone of the sector's sustainability strategy. However, success will require bold commitments, significant investments, and a collective effort to align priorities and actions.

In conclusion, SAF is more than just a technical solution—it embodies the aviation industry's commitment to addressing climate change and fostering innovation. While the road to widespread adoption is filled with challenges, these obstacles are not insurmountable. By addressing these barriers through coordinated global action, investing in research and infrastructure, and fostering public and political support, SAF can fulfill its promise as a key driver of a sustainable aviation future. The benefits of SAF adoption extend beyond environmental impact, offering long-term economic and social advantages that can redefine the future of air travel.

8.1 Recommendations

To promote the adoption and production of SAF, governments should create strong regulatory frameworks that provide consistent financial incentives, such as tax credits and subsidies, to reduce the cost gap between SAF and conventional jet fuel. Harmonizing regulations across countries is also essential to encourage global collaboration and create equal opportunities for airlines and fuel producers.

Carbon credits can also play a vital role in accelerating SAF adoption by offering financial rewards for reducing carbon emissions. Governments and regulatory bodies can expand carbon credit markets to include SAF production, providing fuel producers with additional revenue streams for their environmental contributions. Airlines could benefit from purchasing SAF as part of their emissions reduction strategies, allowing them to offset their carbon footprints and meet regulatory requirements such as CORSIA.

Fuel producers and technology developers must focus on improving SAF production methods by investing in research and development. Efforts should aim to increase feedstock efficiency, advance pathways like HEFA, FT, and ATJ, and scale emerging technologies. Expanding feedstock sources, including third-generation options like algae, is crucial to ensure a reliable and sustainable supply chain, reducing competition with other industries for resources.

Airlines should lead the way in creating demand for SAF through long-term agreements with producers and clear communication about SAF's environmental benefits. Transparency regarding SAF-related costs is key, particularly when it comes to ticket prices. Airlines can educate passengers about how their contributions to SAF can help offset carbon emissions and support sustainability goals. Offering passengers options to voluntarily pay a small fee to support SAF production, along with clear explanations of how these funds are used, can build trust and engagement.

Passengers also play an important role in promoting sustainability. Airlines could introduce tools like carbon impact calculators during the booking process to show passengers the environmental impact of their flights. Loyalty programs could further encourage passengers to opt into these carbon offset contributions, fostering greater participation in sustainable travel. Public campaigns explaining the importance of SAF and its role in reducing aviation emissions can increase awareness and support for its adoption.

The financial sector has a key role in supporting SAF development by offering financing options such as sustainability-linked loans or green bonds. Incentives like discounts tied to the environmental credentials of feedstocks or production methods can encourage producers to adopt more sustainable practices. Banks and investors should also provide capital for scaling up SAF projects and infrastructure to accelerate production.

International organizations, NGOs, and industry bodies should work together to develop consistent global standards for SAF certification, lifecycle emissions assessments, and feedstock sustainability. Coordination among stakeholders will prevent market fragmentation and ensure SAF is adopted on a global scale.

In summary, making SAF a viable solution for aviation requires collaboration among governments, producers, airlines, passengers, financial institutions, and international organizations. By addressing key challenges, such as production costs, regulatory support, and consumer engagement, the aviation industry can significantly reduce its environmental impact and move toward a more sustainable future. Simplified communication, technological innovation, and global cooperation will be vital in achieving this transformation.

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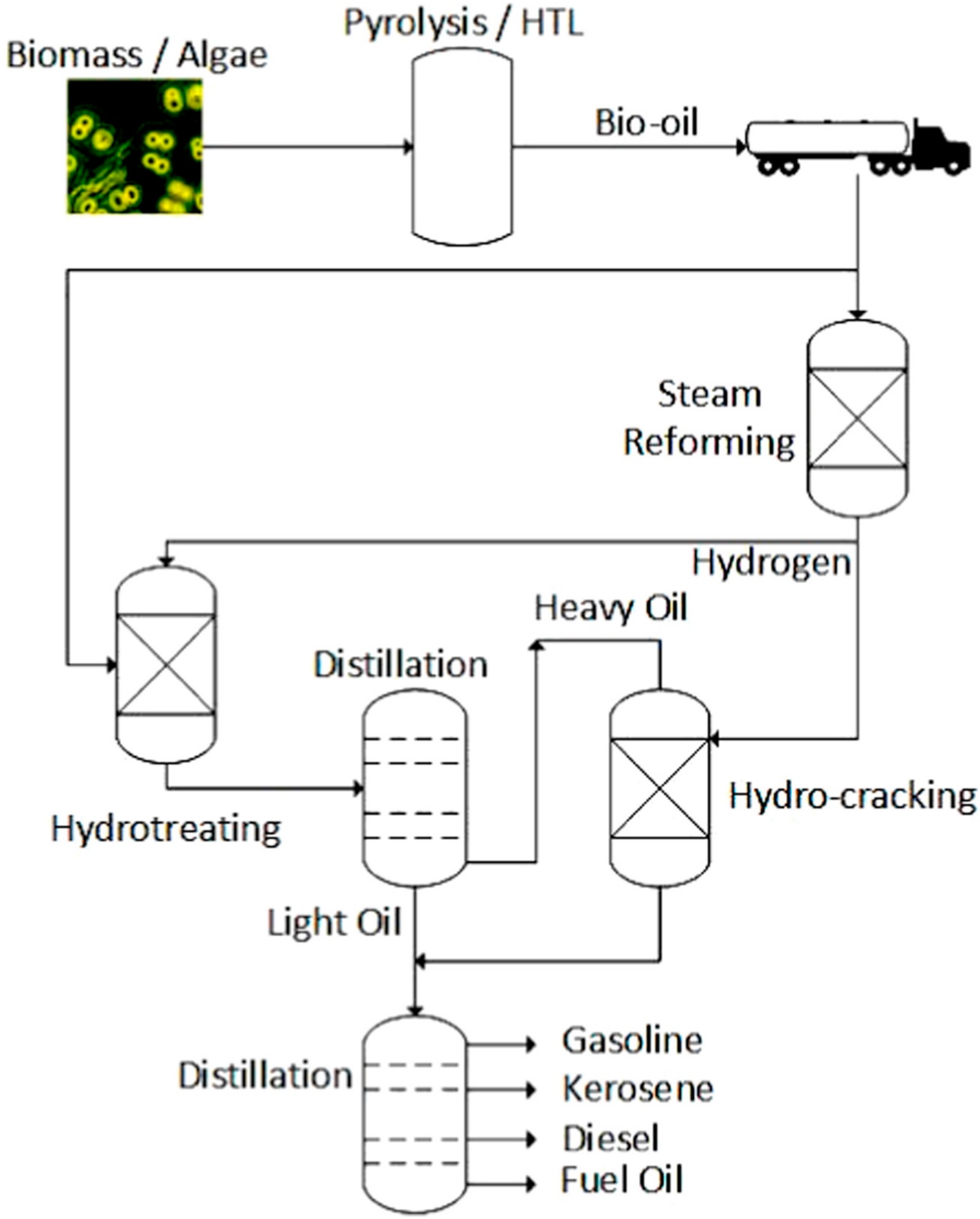
Appendix 1: List of Authorized Feedstocks in the CORSIA Framework

Feedstock	Classification	Reference
Palm fatty acid distillate	By-product	Table 1, ICAO document "Actual LCA methodology" Table 2, ICAO document "Default LCA values"
Technical Corn oil	By-product	Table 1, ICAO document "Actual LCA methodology" Table 2, ICAO document "Default LCA values"
Tallow	By-product	Table 2, ICAO document "Default LCA values"
Beef Tallow	By-product	Table 1, ICAO document "Actual LCA methodology"
Non-Standard Coconuts	By-product	Table 1, ICAO document "Actual LCA methodology"
Poultry Fat	By-product	Table 1, ICAO document "Actual LCA methodology"
Lard Fat	By-product	Table 1, ICAO document "Actual LCA methodology"
Mixed Animals Fat	By-product	Table 1, ICAO document "Actual LCA methodology"
Molasses	co-product	Table 1, ICAO document "Actual LCA methodology" Table 3, ICAO document "Default LCA values"
Brassica carinata oil	Main product	Table 2, ICAO document "Default LCA values"
Camelina oil	Main product	Table 2, ICAO document "Default LCA values"
Corn grain	Main product	Table 3, ICAO document "Default LCA values" Table 4, ICAO document "Default LCA values"
Jatropha oil	Main product	Table 2, ICAO document "Default LCA values"
Miscanthus (herbaceous energy crops)	Main product	Table 1, ICAO document "Default LCA values" Table 3, ICAO document "Default LCA values" Table 4, ICAO document "Default LCA values"
Palm oil	Main product	Table 2, ICAO document "Default LCA values"
Poplar (short-rotation woody crops)	Main product	Table 1, ICAO document "Default LCA values"
Rapeseed oil	Main product	Table 2, ICAO document "Default LCA values"
Soybean oil	Main product	Table 2, ICAO document "Default LCA values" Table 6, ICAO document "Default LCA values"
Sugar beet	Main product	Table 5, ICAO document "Default LCA values"
Sugarcane	Main product	Table 3, ICAO document "Default LCA values" Table 4, ICAO document "Default LCA values" Table 5, ICAO document "Default LCA values"
Switchgrass (herbaceous energy crops)	Main product	Table 1, ICAO document "Default LCA values" Table 3, ICAO document "Default LCA values" Table 4, ICAO document "Default LCA values"
Agricultural residues: Bagasse	Residue	Table 1, ICAO document "Actual LCA methodology"
Agricultural residues: Cobs	Residue	Table 1, ICAO document "Actual LCA methodology"
Agricultural residues: Husks	Residue	Table 1, ICAO document "Actual LCA methodology"
Agricultural residues: Manure	Residue	Table 1, ICAO document "Actual LCA methodology"
Agricultural residues: Nut shells	Residue	Table 1, ICAO document "Actual LCA methodology"
Agricultural residues: Stalks	Residue	Table 1, ICAO document "Actual LCA methodology"
Agricultural residues: Stover	Residue	Table 1, ICAO document "Actual LCA methodology"
Agricultural residues: Straw	Residue	Table 1, ICAO document "Actual LCA methodology"
Forestry residues: Bark	Residue	Table 1, ICAO document "Actual LCA methodology"
Forestry residues: Branches	Residue	Table 1, ICAO document "Actual LCA methodology"
Forestry residues: Cutter shavings	Residue	Table 1, ICAO document "Actual LCA methodology"
Forestry residues: Leaves	Residue	Table 1, ICAO document "Actual LCA methodology"
Forestry residues: Needles	Residue	Table 1, ICAO document "Actual LCA methodology"
Forestry residues: Pre- commercial thinnings	Residue	Table 1, ICAO document "Actual LCA methodology"
Forestry residues: Slash	Residue	Table 1, ICAO document "Actual LCA methodology"
Forestry residues: Tree tops	Residue	Table 1, ICAO document "Actual LCA methodology"
Processing residues: Crude glycerine	Residue	Table 1, ICAO document "Actual LCA methodology"
Processing residues: Crude Tall Oil	Residue	Table 1, ICAO document "Actual LCA methodology"
Processing residues: Empty palm fruit bunches	Residue	Table 1, ICAO document "Actual LCA methodology"
Processing residues: Forestry processing residues	Residue	Table 1, ICAO document "Actual LCA methodology"
Processing residues: Palm oil mill effluent	Residue	Table 1, ICAO document "Actual LCA methodology"
Processing residues: Sewage sludge	Residue	Table 1, ICAO document "Actual LCA methodology"
Processing residues: Tall oil pitch	Residue	Table 1, ICAO document "Actual LCA methodology"
Municipal solid waste (MSW)	Waste	Table 1, ICAO document "Default LCA values" Table 1, ICAO document "Actual LCA methodology"
Used cooking oil	Waste	Table 1, ICAO document "Actual LCA methodology" Table 2, ICAO document "Default LCA values" Table 6, ICAO document "Default LCA values"
Waste gases	Waste	Table 1, ICAO document "Actual LCA methodology" Table 4, ICAO document "Default LCA values"
Wheat starch slurry	Residue	Table 1, ICAO document "Actual LCA methodology"

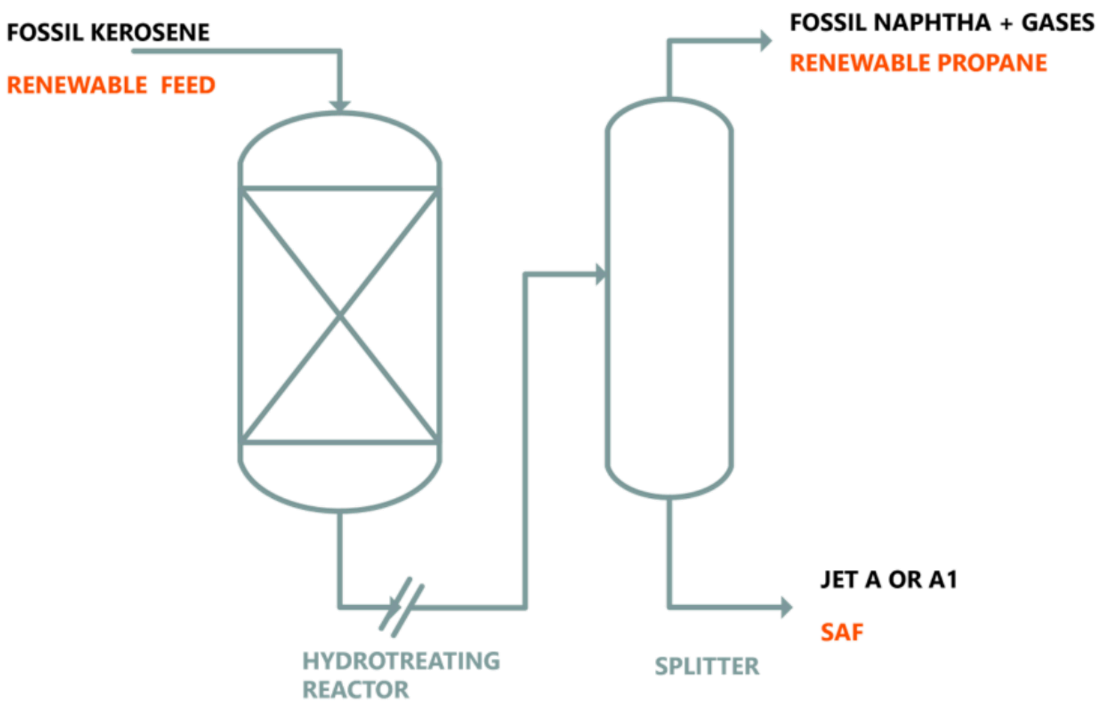
(*ICAO Guidance on Policy Measures for SAF Development and Deployment*, n.d.-a)

Appendix 2: The Hydroprocess



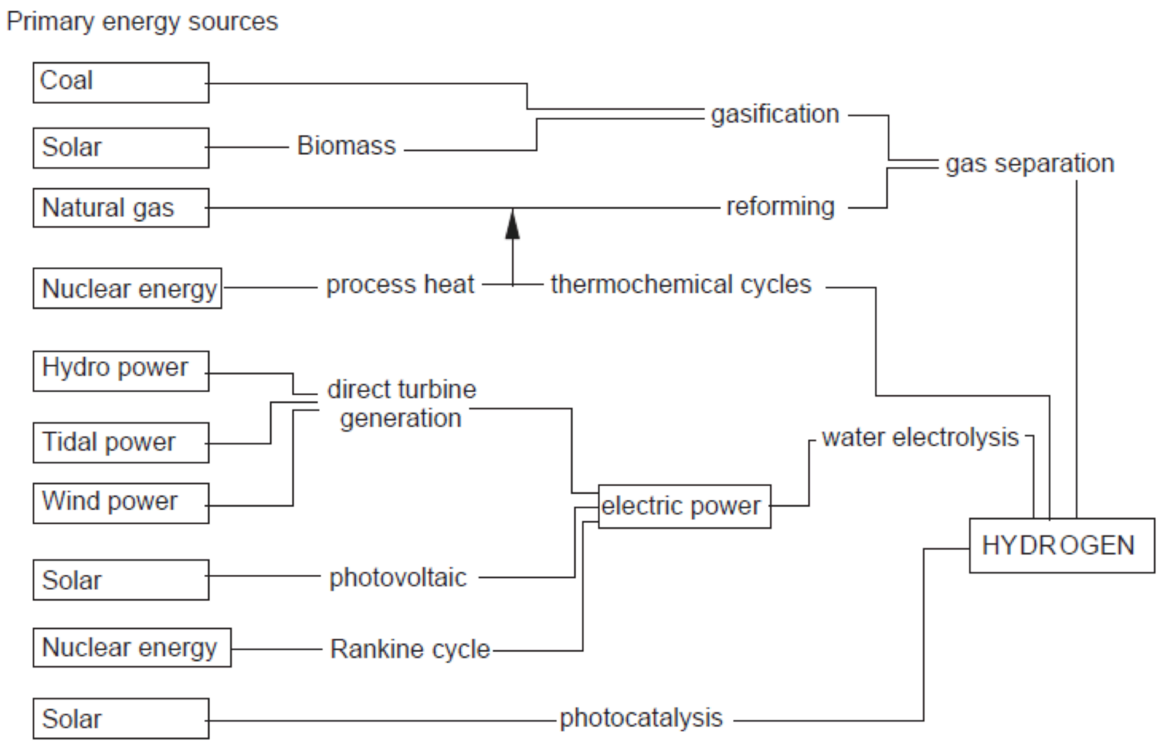
(Saber et al., 2016)

Appendix 3: Co-processing



(Co-Processing, n.d.)

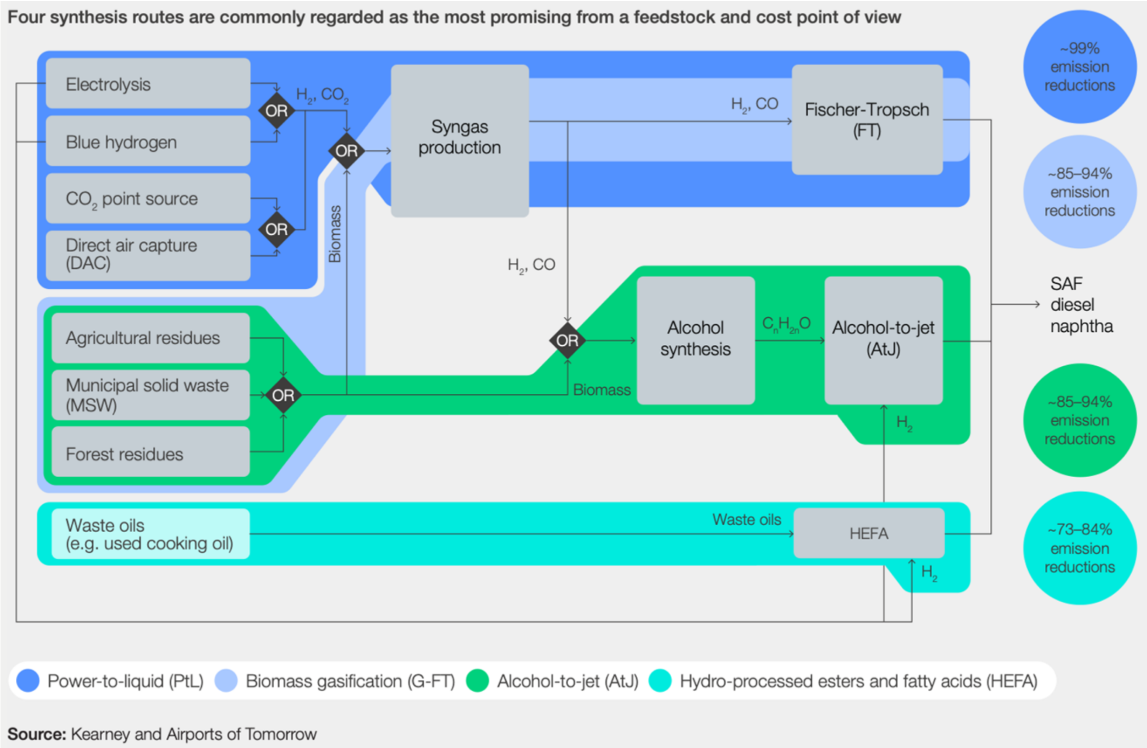
Appendix 4: Routes for Hydrogen manufacture



(*IATA Hydrogen Factsheet*, n.d.)

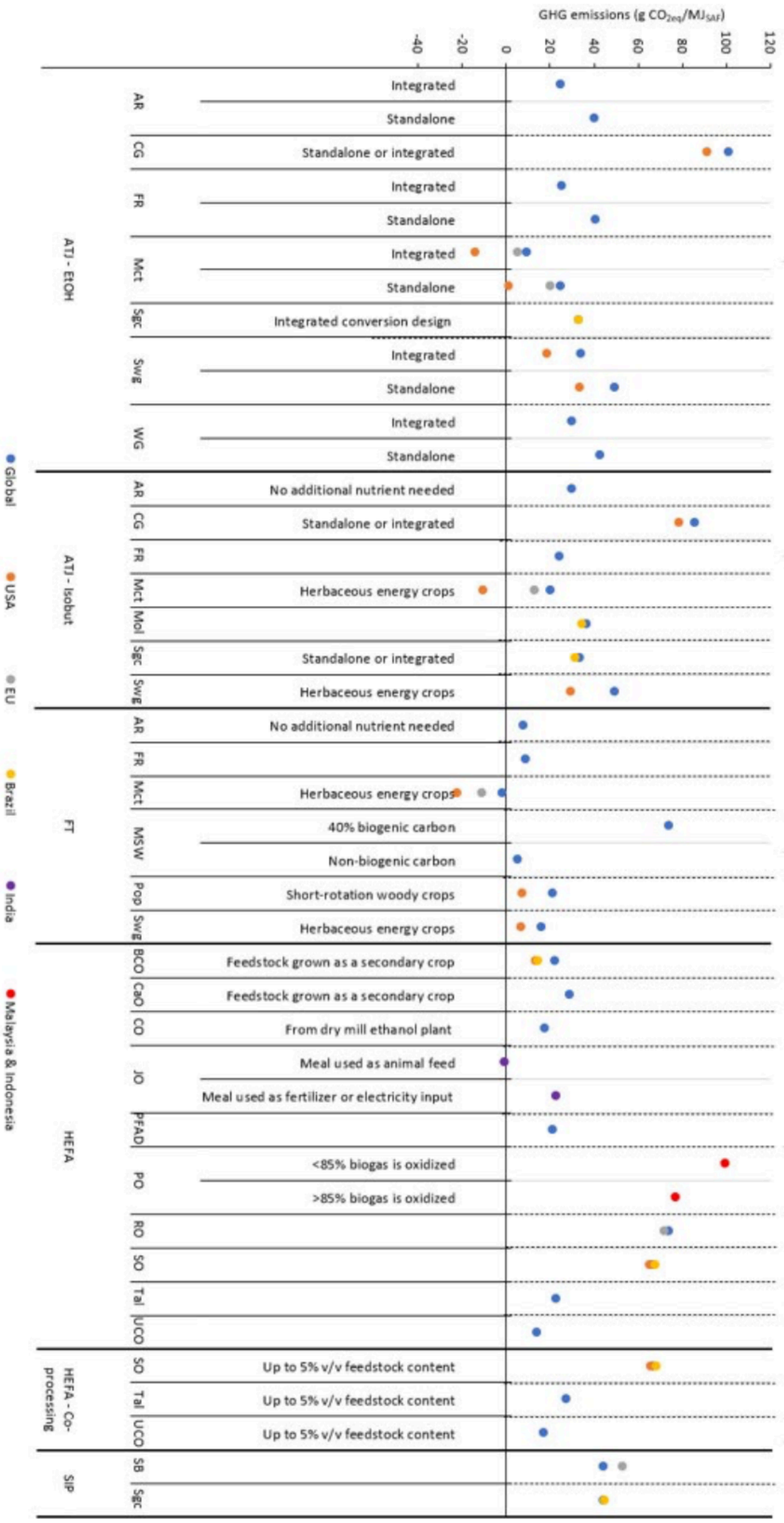
Appendix 5: Projected Emission Reductions per Pathway

The four leading ASTM-approved pathways anticipated for large-scale deployment in the coming decades, especially as per the promise shown for emission reductions are HEFA, FT, ATJ and PTL as can be seen below:



(Baroutaji et al., 2019)

Appendix 6: Default Lifecycle GHG Emission Factors under CORSIA



(Malina et al., n.d.)

Appendix 7: Detailed Overview of SAF Policies

Appendix A – Table of SAF Policy Options

Impact Area	Policy Category	Policy Option	Description
Stimulating Growth of SAF Supply	1 - Public funding for SAF research, development, demonstration and deployment (RDD&D) to accelerate learning	1.1 - Public funding for R&D	Research grants and public funding to address barriers to SAF production and use can help early stage SAF production innovations. It also supports SAF economics by accelerating the learning curve for feedstock yields or production optimisation. Support can occur from establishing specific programs or supporting existing private research activities or through universities or similar institutions.
		1.2 - Public funding for demonstration and deployment	Research grants and public funding to demonstrate and de-risk new feedstock and conversion technologies can provide support to both feedstock and fuel technology providers to scale up and integrate their production. This support accelerates the learning process around technology and supply chain scale up. Support can occur from establishing specific programs that support existing private sector producers.
	2 - Targeted incentives and tax relief to expand SAF supply infrastructure	2.1 - Capital grants	A government grant given to an entity to build or buy SAF-specific infrastructure. This can support a range of production facilities, transportation, re-fuelling or blending infrastructure. Capital grants reduce the financial needs and financial risks of the targeted investment.
		2.2 - Loan guarantee programs	A loan backed by a government or public institution helps the project financial case, and also reduces overall project risk, making acquiring additional equity of debt easier and lowers cost of capital.
		2.3 - Eligibility of SAF projects for tax advantaged business status	For example master limited partnerships (MLPs) are a specialized U.S. business organization type that is limited in use to the real estate and natural resources sectors (e.g. oil production). MLPs do not pay federal income taxes in the same way that other corporate structures do.
		2.4 - Accelerated depreciation/'bonus' depreciation	Accelerated or bonus depreciation allows the accounting write-off of capital investment or the potential to write off more than the actual capital investment. This will result in less expected tax to be paid over the life of the project and improve overall project economics.
		2.5 - Business Investment Tax Credit (ITC) for SAF investments	An ITC tax credit allows deduction of construction and/or commissioning costs of a qualifying asset which can reduce income tax payable and flow through to investors. This will result in less expected tax to be paid over the life of the project and improve overall project economics.
		2.6 - Performance-based tax credit	The concept offers a tax credit for a project meeting certain conditions. The credit could be a sliding scale performance credit (higher credit for better GHG performing projects) and should have a defined policy life (i.e. 10-15 years).
		2.7 – Bonds / Green Bonds	Bonds can be issued by private companies, supranational institutions, and public entities including sub-national and local governments to provide low-interest rate and tax exempt financing used to support fuel production infrastructure build out. Green Bonds are designed specifically to support specific climate-related or environmental projects.
		2.8 – Simplify administrative procedures	Review of the approval rules for establishing of industrial plants for feedstock/inputs production as well as for SAF production to simplify administrative procedure and reduce the time required to establish industrial capacities
		2.9 – De-risking supply	For example, the European Hydrogen Bank is a financing instrument designed to unlock private investments in hydrogen value chains, both domestically and in third countries, by connecting renewable energy supply to EU demand and addressing the initial investment challenges.
	3 - Targeted incentives and tax relief to assist SAF facility operation	3.1 Blending incentives: Blender's Tax Credit	An incentive targeted at the providers or blenders of fuel that provides a credit against taxes. This mitigates the blenders cost of production or purchase difference between SAF and fossil jet.
		3.2 – Production incentives: Producer's Tax Credit	An incentive targeted at the producers of fuels that provides a credit against taxes. This mitigates the cost of production difference between SAF and fossil jet.

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		3.3 - Excise tax credit for SAF	For States that tax domestic jet fuel consumption, a reduction or elimination of the tax in proportion to quantity of SAF consumed serves to incentivize fuel consumers to purchase SAF by contributing to lower SAF cost.
		3.4 - Support for feedstock supply establishment and production	Targeted support can address the risks and costs to farmers and feedstock suppliers of establishing a new crop and producing it under uncertain conditions. Crop insurance program support for SAF can also be considered in addition to subsidy payments made to farmers aimed at incentivizing production.
		3.5 – Reducing the price gap between SAF and fossil fuel for end user	Targeted support to the end user can help address the cost issue and support airlines to procure more SAF by covering a certain amount of the price different between SAF and fossil jet fuel
	4 - Recognition and valorization of SAF environmental benefits	4.1 – Recognize SAF benefits under carbon taxation	Where a jurisdiction has introduced a carbon tax, carbon price, or carbon levy (that is setting a tax rate on carbon emissions for each fuel type, thereby providing a signal to reduce emissions) SAF could be rated as either zero or in proportion to the life-cycle greenhouse gas emissions benefit of the particular fuel, thereby subject to reduced tax. This differs from a cap and trade system by not stipulating an overall emission reduction target.
		4.2 - Recognize SAF benefits under cap-and-trade systems	Cap-and-trade systems limit total GHG emissions by setting a maximum emissions level and allowing participants with lower emissions to sell surplus emission permits to larger emitters. This system creates supply and demand for emissions permits and establishes a market price for emissions and a value for avoided emissions. If SAF were used in such a system, it would exempt the user of the SAF of obligations under the regulation.
		4.3 - Recognize non-CO_2 SAF benefits: improvements to air quality	Some programs and incentives place a value on local air quality. SAF should be able to financially participate in these incentive schemes based on air quality benefits that certain SAFs may be able to provide.
Creating Demand for SAF	**5- Creation of SAF mandates**	5.1 - Mandate SAF energy volume requirements in the fuel supply	An obligation on fuel providers to provide increasing SAF fuel volumes added to the existing fuel supply on a multi-year schedule creates an incentive for production of more SAF and other fuels which meet the renewable energy definitions of the program. These definitions can include life-cycle greenhouse gas emissions requirements.
		5.2 - Mandate reduction in carbon intensity of the fuel supply	An obligation on fuel providers to reduce the carbon intensity (life-cycle greenhouse gas emissions intensity) of the transportation fuel supply on a multi-year schedule creates an incentive for production of more SAF and other fuels with greenhouse gas benefits. Low carbon fuel standards (LCFS) and clean fuels standards can enable targeting of the carbon intensity of the State's fuel supply.
		5.3 – Mandate reduction in carbon intensity of the fuel uptake	An obligation on aircraft operators to reduce the carbon intensity (life-cycle greenhouse gas emissions intensity) of their operations through the transportation fuel they buy, on a multi-year schedule, which fosters the competition among fuels producers for the use of the best technology available and the most efficient SAF and cleaner fuels.
		5.4 – Requirement for end users to support SAF use	A requirement on air transport users to pay for SAF use, in line with the user pays principle. It provides transparency to consumers, and ensures a level-playing field as consumers pay based on the amounts consumed (e.g. proportionate to flight lengths and class of travel). It also provides for a long-term financially sustainable approach to generate SAF demand as costs are borne by the aviation system. This may not necessarily be a mandate
	6 - Update existing policies to incorporate SAF	6.1: Incorporating SAF into existing national policies	Many national level policies may be adapted to incorporate SAF. Typically, legacy biofuel policies have focused on road-transport-appropriate fuels and do not include SAF as an option. With the more recent advent of drop-in jet fuel/SAF production technologies, an opportunity exists to update existing policies to support SAF production.
		6.2: Incorporating SAF into existing sub-national, regional or local policies	Existing alternative fuel incentive policies at a sub-national, regional or local level may be abler to to incorporate SAF as qualified fuels. An update to these existing policies to support SAF production can provide additional support and may enable a beneficial "stacking" of incentives at multiple levels that contributes to SAF economic viability.
	7 – Demonstrate government leadership	7.1 Policy statement to establish direction	Setting aspirational goals of specific production or use amounts to signal future intent to develop comprehensive SAF policy measures. This can be linked to the implementation of future policies, sending a signal for project planning. Examples could include State level commitments for a quantitative SAF use goal or carbon reduction by a certain time, or signals from industry such as a commitment to achieve net zero by 2050.

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		7.2: Government commitment to SAF use, carbon neutral air travel	A strong demand signal can be created by requiring national, state, local governments, and military to commit to renewable fuel/SAF procurement to reduce environmental impacts of air travel and operations. Governments often have the ability to commit to long term contracts backed by strong credit rating which lowers project risk. Governments can either directly purchase SAF for use by government aircraft or contract with commercial air carriers to provide SAF to power government purchased travel.
Enabling SAF Markets	**8 - Market enabling activities**	8.1 - Adopt clear and recognized sustainability standards and life cycle GHG emissions methods for certification of feedstock supply and fuel production	Use of clear standards and harmonized methods for life cycle GHG emissions calculation and sustainability certification will support broad SAF markets and ensure environmental integrity.
		8.2 - Support development/recognition of systems for environmental attribute ownership and transfer	Standard processes and shared systems for calculating, crediting and trading the environmental attributes of SAF may facilitate "book and claim" purchasing of SAF that decouples the physical fuel location and the environmental benefit in order to facilitate and promote more efficient and broader use of SAF volumes and their GHG emission reductions.
		8.3 - Support SAF stakeholder initiatives	Stakeholder consultation groups can take many forms and be either government, industry or NGO led. These groups serve a critical function of aligning the diverse stakeholders that make up the SAF supply chain. They can directly coordinate actions and provide critical information and feedback to policymakers. The implementation of common environmental label to allow passengers to make informed choices regarding the sustainability of flights can directly support stakeholders' actions and SAF procurement by airlines
		8.4 – Support the qualification of new SAF production pathways	SAF Clearing House concepts will help to accelerate and reduce costs of the standardization processes, including technical suitability and production scalability, thus helping SAF producers to access financial support and increasing the availability of SAF on the market.

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(*ICAO Guidance on Policy Measures for SAF Development and Deployment*, n.d.-b)