

RECENT ADVANCES IN SUSTAINABLE AVIATION FUEL TECHNOLOGY



Source: Orient Flights

Introduction

Sustainable aviation fuels (SAFs) are at the forefront of the aviation industry's efforts to reduce its environmental impact. As the world grapples with climate change, the aviation sector, which accounts for 2-3 percent of global carbon dioxide emissions, has been seeking sustainable alternatives to conventional jet fuels¹. SAFs have emerged as a promising solution, offering the potential to significantly reduce greenhouse gas emissions and contribute to the industry's long-term sustainability goals. The adoption of SAFs has notably increased globally in recent years, and production capacity is expected to double from 7 million metric tons in 2022 to 14 million metric tons by 2030¹. This growth is driven by advancements in technology, increased investment, and supportive government policies. Several major airlines have already committed to incorporating SAFs into their operations, and new production facilities are being established worldwide to meet the rising demand.

Societal and Global Impact

The societal and global impact of sustainable aviation fuels extends beyond environmental benefits. The development and deployment of SAFs can stimulate economic growth by creating new jobs in the biofuel production and supply chain sectors. According to the World Economic Forum, the SAF industry has the potential to generate thousands of jobs globally, particularly in rural areas where feedstock production and biofuel processing facilities are often located¹. Moreover, SAFs can enhance energy security by reducing dependence on fossil fuels. By diversifying the energy sources used in aviation, countries can mitigate the risks associated with volatile oil prices and geopolitical tensions. This diversification is particularly important for regions that are heavily reliant on imported fossil fuels. The International Civil Aviation Organization (ICAO) highlights that SAFs can play a key role in achieving global aspirational goals for international aviation, contributing to both environmental sustainability and economic resilience².

Environmental Impact

The environmental impact of SAFs is immense, as they offer a significant reduction in greenhouse gas emissions compared to conventional jet fuels. This reduction is achieved using renewable and waste-derived feedstocks, which recycle carbon that is already present in the atmosphere, rather than releasing new carbon from fossil sources. Additionally, SAFs can improve local air quality by reducing emissions of particulate matter by up to 90 percent and sulfur oxides by up to 100 percent²⁴, which are harmful pollutants associated with conventional jet fuels. SAFs also have the potential to reduce non-CO₂ emissions, such as nitrogen oxides (NOx) and soot particles, by up to 50-70 percent²⁴, which contributes to climate change and has adverse health effects. Sustainable aviation fuels (SAFs) reduce NOx and soot emissions because they contain fewer impurities, such as sulfur and aromatic compounds, compared to conventional jet fuels, leading to cleaner combustion and fewer byproducts²⁶.

This graph depicts that 25 percent of emissions from aviation can be reduced by SAFs. A study by the Roundtable on Sustainable Biomaterials (RSB) found that high blends of SAFs can significantly reduce non-CO₂ emissions, thereby enhancing both global and local environmental benefits. Furthermore, using SAFs can help mitigate the formation of contrails and cirrus clouds, which have a drastic warming effect on the climate. Research indicates that SAFs can reduce contrail formation by up to 50-70 percent, contributing to a lower overall climate impact from aviation²⁴. To achieve these results, SAFs are typically blended with conventional jet fuel in proportions ranging from 10 percent to 50 percent²⁷.

Key Technologies

Hydro processed Esters and Fatty Acids (HEFA)

Hydro-processed Esters and Fatty Acids (HEFA)-based SAFs use feedstocks such as cooking oil, animal fats, and other waste oils. The HEFA process involves hydrogenating and

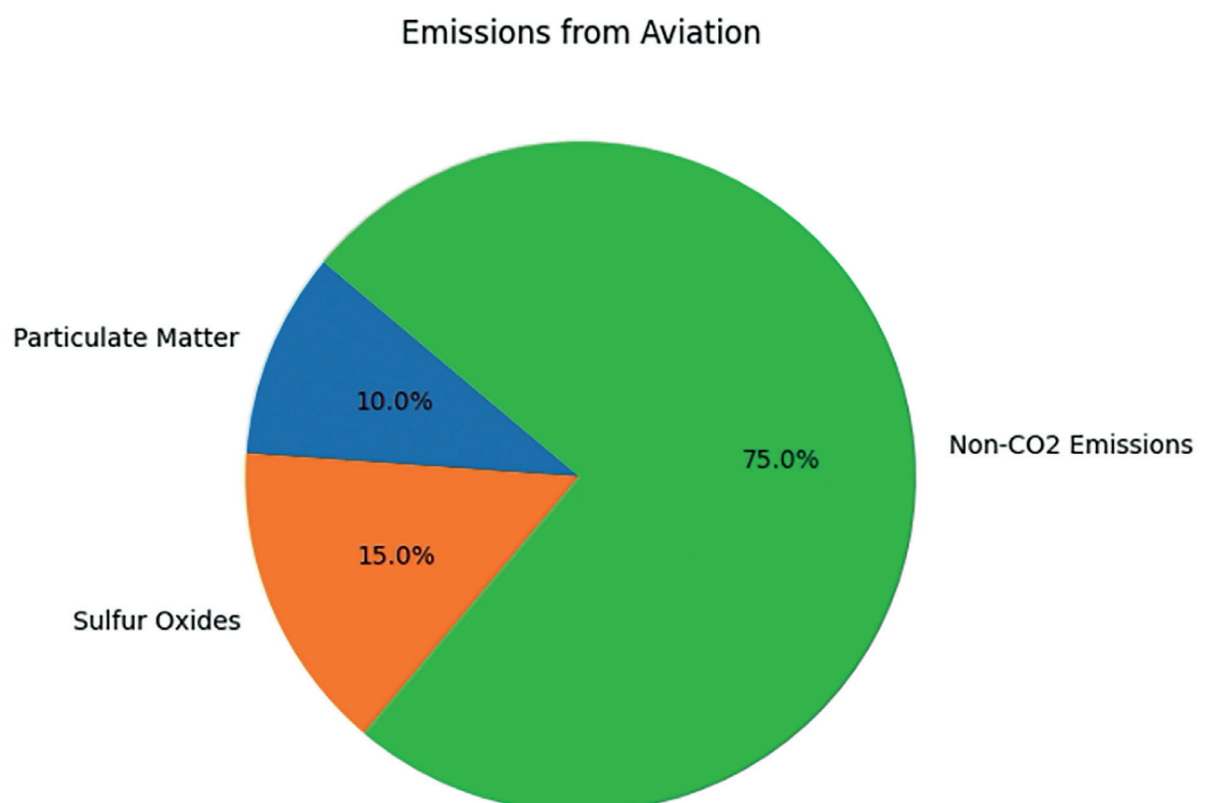


Figure 1. Aviation Emission statistics²⁴

deoxygenating these feedstocks to produce hydrocarbons like conventional jet fuel. HEFA is currently the most commercially viable SAF technology, with over 20 facilities globally that produce HEFA-based jet fuels. The chemistry behind HEFA involves the hydrotreatment of triglycerides and fatty acids, which are reacted with hydrogen under high pressure to remove oxygen, resulting in hydrocarbon chains chemically equivalent to petroleum diesel¹⁵. HEFA fuels are used by various airlines for commercial flights, with companies like Neste leading the production.

Recent studies have shown that HEFA fuels can reduce lifecycle greenhouse gas emissions by up to 80 percent compared to conventional jet fuels. The study by Zhang et al. aimed to evaluate the performance and emission characteristics of a Jet A-1/HEFA blend in a miniature turbojet engine. The study found that the Jet A-1/HEFA blend resulted in lower CO emissions and fuel consumption compared to conventional Jet A-1 fuel, highlighting the potential environmental benefits of HEFA fuels. The following table summarizes the key aspects and benefits of HEFA fuels. The advancements and research in HEFA technology underscore their critical role in the transition towards more sustainable aviation fuels, offering significant environmental benefits and practical applications in the aviation industry.

Alcohol-to-Jet (ATJ)

Alcohol-to-jet (ATJ) technology utilizes biomass-derived alcohols such as ethanol and butanol. The process involves dehydrating the alcohols to form olefins, which are then oligomerized and hydrogenated to produce jet fuel. ATJ can utilize a wide range of biomass sources, making it a flexible option for SAF production. The chemistry behind ATJ involves catalytic steps historically used in the petroleum refining industry, converting alcohols into long-chain hydrocarbons suitable for jet fuel. ATJ fuels are used by airlines and supported by companies like Lanza Jet, which has made significant strides in commercializing this technology. Studies have indicated that ATJ fuels can achieve a reduction in greenhouse gas emissions of up to 70 percent compared to conventional jet fuels.

One study by Geleynse et al. was to provide an economic evaluation of the ATJ conversion pathway for producing drop-in biofuels. The study found that the utilization of isobutanol offers a 34 percent lower conversion cost for the catalytic upgrading process compared to ethanol². Another study by Yao et al. aimed to conduct a stochastic techno-economic analysis of ATJ fuel production, focusing on the uncertainties in feedstock costs, conversion efficiencies, and market prices. The study showed that sugarcane is the lowest-cost feedstock with the least risks, followed by corn grain and switchgrass, with mean breakeven jet fuel prices of \$0.96/L, \$1.01/L, and \$1.38/L, respectively²³. This contributes to understanding the economic risks and benefits associated with ATJ fuel production, providing valuable insights for investors and policymakers to support the development and commercialization of ATJ fuels. The advancements and research in ATJ technology highlight its potential as a versatile and economically viable solution for sustainable aviation fuel production, significantly contributing to the reduction of greenhouse gas emissions in the aviation industry.

Fischer-Tropsch (FT) Synthesis

Fischer-Tropsch (FT) synthesis uses feedstocks like biomass, municipal solid waste, and other carbon-rich materials. These feedstocks are gasified to produce syngas, a mixture of hydrogen and carbon monoxide, which is then converted into liquid hydrocarbons through the FT process. FT can produce high-quality jet fuel and other valuable co-products. The chemistry behind FT involves the catalytic conversion of syngas into hydrocarbons, a process that can be tailored to produce specific types of fuels. FT fuels are used by various industries, including aviation, with companies like Velocys optimizing the process for SAF production.

Research has demonstrated that FT fuels can reduce lifecycle greenhouse gas emissions by up to 90 percent compared to conventional jet fuels²¹. One study by Chai et al. provided a detailed mechanistic understanding of FT synthesis on Fe-carbide catalysts, focusing on the kinetic and mechanistic aspects of the process. The study found that the Fe-carbide catalysts exhibited a 15 percent increase in selectivity for long-chain hydrocarbons⁵. Another study by Mahmoudi et al. (2017) aimed to review the FT processes, including the

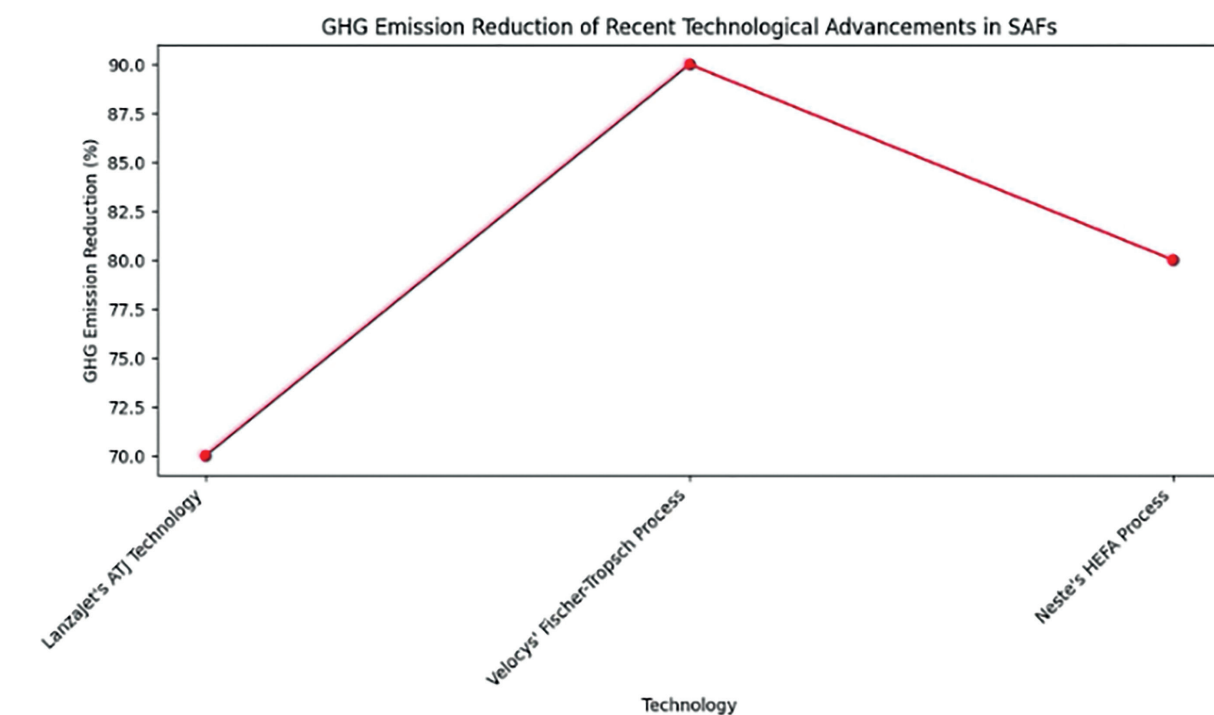


Figure 2. This graph compares the efficacy of three technologies in terms of their GHG Emission Reduction

mechanisms, surface chemistry, and catalyst formulation. The study highlighted that the optimized catalyst formulation could achieve a 20 percent increase in conversion efficiency⁶. Its comprehensive overview of the FT process can guide future research and development efforts to optimize catalyst performance and reactor design, ultimately supporting the large-scale production of FT fuels and their adoption in the aviation industry. The progress and research in FT synthesis highlight its potential to transform sustainable aviation fuel production, providing significant environmental advantages and facilitating its wider adoption in the aviation sector.

Pyrolysis

Pyrolysis involves heating biomass and waste materials in the absence of oxygen to produce bio-oil, which can be refined to jet fuel. Pyrolysis can handle a wide variety of feedstocks and produce multiple types of biofuels. The chemistry behind pyrolysis involves the thermal decomposition of organic materials, resulting in the production of gases, liquids, and solid residues. Pyrolysis fuels are used in various applications, including aviation, with ongoing research to improve the efficiency and scalability of the process. Studies have shown that pyrolysis-based SAFs can achieve significant reductions in greenhouse gas emissions, depending on the feedstock and process conditions.

One such study by Watanasiri et al. explored the potential of catalytic fast pyrolysis (CFP) to produce SAFs. This research focuses on the catalytic fast pyrolysis of biomass, including wood, woody residues, and agricultural waste, to generate organic liquid intermediates. The study's primary objective was to predict the properties of SAF fuels derived from the hydroprocessing of CFP-based oxygenated organic intermediates. The impact of this study on the field of sustainable aviation fuels is significant. Firstly, it demonstrates the viability of using biomass and waste materials as feedstocks for SAF production, which can help reduce reliance on fossil fuels and lower greenhouse gas emissions. The use of catalytic fast pyrolysis to convert these feedstocks into organic intermediates offers a promising pathway for producing high-quality SAFs. Additionally, the study's focus on property predictions provides a framework for evaluating the performance and suitability of CFP-derived SAFs, which is crucial for their adoption in the aviation industry. The study found that the SAF produced had a carbon yield of 28 percent during the CFP process and an overall carbon yield to SAF of 11 percent, which provides valuable insights into the production and properties of SAFs derived from catalytic fast pyrolysis of biomass. It highlights the potential of this technology to contribute to the development of sustainable aviation fuels, offering a pathway to reduce the aviation sector's carbon footprint and enhance energy security. The progress in pyrolysis technology highlights its potential to play a crucial role in producing sustainable aviation fuels, thereby helping to reduce the aviation industry's carbon footprint and improve energy security.

Power-to-Liquid Fuels

Power-to-liquid (PtL) technology uses renewable electricity, water, and captured carbon dioxide as feedstocks. The process involves splitting water into hydrogen and oxygen using renewable electricity (electrolysis). The hydrogen is then combined with captured CO₂ to produce hydrocarbons through the Fischer-Tropsch process. PtL fuels can achieve near-zero or even negative carbon emissions, depending on the source of electricity and CO₂. Electrofuels (E-fuels) are produced using a similar process, combining hydrogen (from water electrolysis) with CO₂ to create synthetic hydrocarbons. E-fuels offer a sustainable alternative to fossil fuels and can be produced using excess renewable energy. E-fuels and Power-to-Liquid (PtL) fuels are synthetic fuels produced using renewable electricity and captured CO₂, but they differ mainly in their applications and production processes. E-fuels encompass a broad category of synthetic fuels, including e-diesel, e-gasoline, and e-jet fuel, designed to be used in existing internal combustion engines and infrastructure without modifications. This versatility makes them suitable for various transport sectors, such as aviation, marine, and heavy-duty road transport. In contrast, PtL fuels specifically refer to liquid hydrocarbons produced through the Fischer-Tropsch (FT) process, primarily aimed at replacing conventional jet fuels in aviation. PtL fuels can be blended with traditional kerosene and transported using existing fossil fuel infrastructure. Thus, while both e-fuels and PtL fuels are produced using similar processes, e-fuels offer a wider range of applications, whereas PtL fuels are tailored specifically for aviation use.

Recent advancements in PtL technology have shown promise in reducing production costs and improving efficiency. The main objective of the study by Schmidt et al. was to explore the potential and perspectives for the future supply of renewable aviation fuel through PtL technology²⁰. The study by Brynolf et al. aimed to review the production costs of electrofuels for the transport sector, including PtL fuels²¹. They found that while current production costs are high, ongoing technological advancements and economies of scale could make electro-fuels more competitive with conventional fuels in the future. For example, Brynolf et al. found that production costs for PtL fuels could decrease by up to 50 percent with technological advancements and increased production scale. Ultimately, the progress in PtL and electro-fuel technologies underscores their potential to transform the aviation sector by offering sustainable and cost-effective alternatives to traditional jet fuels.

Recent Technological Advancements

Recent technological advancements in the past two years have further propelled the development of SAFs. Synhelion has developed a unique process to produce carbon-neutral solar fuels using concentrated solar energy to drive thermochemical reactions. This technology has the potential to produce SAFs with a significantly lower carbon footprint by utilizing solar

energy directly. According to a study published in the journal *Nature Energy*, Synhelion's solar-driven thermochemical process can achieve conversion efficiencies of up to 20 percent, making it a highly efficient method for producing SAFs⁹. This breakthrough has the potential to revolutionize the SAF industry by providing a sustainable and scalable production method.

LanzaJet has made significant strides in commercializing its ATJ technology, which converts ethanol into jet fuel. The company has secured funding and partnerships to scale up production, with plans to produce millions of gallons of SAF annually. A recent study in the *Journal of Cleaner Production* highlighted LanzaJet's advancements in ATJ technology, noting that the company's process can achieve a 70 percent reduction in greenhouse gas emissions compared to conventional jet fuels¹⁰. This makes ATJ a promising option for reducing the aviation industry's carbon footprint. Velocys has optimized its Fischer-Tropsch process to convert municipal solid waste and other feedstocks into SAF. The company has received regulatory approvals and is constructing commercial-scale facilities to produce SAF from waste materials. Research published in *Renewable and Sustainable Energy Reviews* has shown that Velocys' FT process can achieve high conversion efficiencies and produce high-quality jet fuel with a 90 percent reduction in lifecycle greenhouse gas emissions¹¹. This demonstrates the potential of FT synthesis to contribute significantly to the aviation industry's decarbonization efforts. Neste, a leading producer of HEFA-based SAF, has expanded its production capacity significantly. Neste's new facilities in Singapore and the Netherlands are expected to increase global SAF supply and reduce production costs. A study in the *Journal of Industrial Ecology* reported that Neste's HEFA process can reduce greenhouse gas emissions by up to 80 percent compared to conventional jet fuels¹². The expansion of Neste's production capacity is a critical step towards meeting the growing demand for SAFs and achieving the aviation industry's sustainability goals. In conclusion, these technological advancements and increased production capacities underscore the significant potential of SAFs to revolutionize the aviation industry, offering sustainable solutions that drastically reduce greenhouse gas emissions and support global sustainability goals.

This graph compares the various technologies based on their GHG Emission Reduction. As depicted by the graph, the Fischer-Tropsch Process is the most efficient of the three processes.

Challenges and Solutions

High Production Costs

One of the primary challenges facing SAFs is the high production cost. SAFs are currently more expensive to produce than conventional jet fuels, primarily due to the complexity of the production processes and the limited availability of feedstocks. The production of SAFs involves advanced technologies all of which require significant capital investment and operational costs⁹. According to a report by the International Air Transport Association (IATA), the cost of SAFs can be up to three times higher than that of conventional jet fuels. To address the high production costs, several strategies are being implemented. Technological advancements are playing a crucial role in improving the efficiency of SAF production processes. For instance, innovations in catalytic conversion technologies and feedstock processing are helping to reduce costs. Additionally, economies of scale can be achieved by increasing production volumes, which can lower the per-unit cost of SAFs. Government incentives and subsidies are also essential in bridging the cost gap between SAFs and conventional jet fuels. Policies such as tax credits, grants, and blending mandates can encourage investment in SAF production and make these fuels more economically viable.

Scalability

Scaling up SAF production to meet global demand is a significant challenge. Current production levels are insufficient to meet the aviation industry's fuel requirements, and substantial investment in infrastructure and technology is needed to increase production capacity. The International Energy Agency (IEA) estimates that to meet the aviation sector's decarbonization goals, SAF production needs to increase from less than 0.1 percent of total aviation fuel consumption in 2020 to around 10 percent by 2037¹⁷. Currently,

Table 2: Summarization of the Challenges with SAFs

Challenges	Specifications
High Production Costs	SAFs are currently more expensive to produce than conventional jet fuels, primarily due to the complexity of the production processes and the limited availability of feedstock. The cost of SAFs can be up to three times higher than that of conventional jet fuels
Scalability	Scaling up SAF production to meet global demand is a significant challenge. Current production levels are insufficient to meet the aviation industry's fuel requirement, and substantial investment in infrastructure and technology is needed to increase production capacity

SAF production accounts for only about 0.53 percent of the aviation industry's fuel needs². Public-private partnerships and international collaboration are essential to scale up SAF production. Governments, industry stakeholders, and research institutions need to work together to develop and implement large-scale SAF production facilities.

Conclusion

In conclusion, while SAFs offer a promising solution to reduce the aviation industry's carbon footprint, several challenges need to be addressed to achieve widespread adoption. High production costs, feedstock availability, and scalability are significant barriers that require coordinated efforts from governments, industry stakeholders, and research institutions. The high production costs of SAFs, primarily due to the complexity of production processes and the limited availability of feedstocks, can be mitigated through technological advancements, economies of scale, and government incentives. Ensuring a consistent and sustainable supply of feedstocks is crucial, and this can be achieved by diversifying feedstock sources and improving logistics and supply chains. Scaling up production to meet global demand necessitates substantial investment in infrastructure and technology, with public-private partnerships and international collaboration playing a key role. Despite these challenges, the benefits of SAFs are substantial, including significant reductions in greenhouse gas emissions, lower CO emissions, and improved fuel efficiency. The advancements and research in SAF technologies underscore their critical role in the transition towards more sustainable aviation fuels. Continued investment in research and development, exploration of new feedstock sources, and supportive policies and regulatory frameworks are essential. By addressing these challenges and leveraging the benefits, the aviation industry can pave the way for a more sustainable future, significantly reducing its environmental impact and supporting global sustainability goals.

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