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# Economic and sustainability challenges in Sustainable Aviation Fuel (SAF) Production and Supply: Aligning with U.S. Decarbonization Goals via LCA, TEA, and Business Perspectives

Irham Tanjung *

*Department of Civil and Environmental Engineering, Cornell University, Ithaca, New York, United States.*

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## Abstract

Sustainable Aviation Fuel (SAF) has emerged as a pivotal solution for decarbonizing the aviation sector, which contributes 2-3% of global $CO_2$ emissions. SAF, derived from renewable feedstocks such as waste oils, agricultural residues, and synthetic fuels, can reduce lifecycle greenhouse gas (GHG) emissions by up to 80% compared to conventional jet fuel. However, its production and supply face significant economic and sustainability challenges, including high costs, limited feedstock availability, and scalability issues. This research employs Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) to evaluate the environmental and economic viability of SAF production pathways. Key findings reveal that feedstock selection and conversion technologies significantly influence SAF's carbon footprint and cost competitiveness. While waste-based feedstocks and advanced pathways like Power-to-Liquid (PtL) offer substantial GHG reductions, their high production costs and infrastructure requirements remain barriers to widespread adoption. Policy mechanisms such as tax credits, carbon pricing, and blending mandates are essential to bridge the cost gap and incentivize SAF production. Additionally, industry collaboration and technological innovation are critical for scaling SAF production and integrating it into existing supply chains. This study underscores the need for a holistic approach, combining robust policy frameworks, sustainable feedstock sourcing, and cross-sector partnerships, to align SAF production with U.S. decarbonization goals and accelerate the transition to a low-carbon aviation sector. Future research should focus on optimizing feedstock logistics, advancing conversion technologies, and assessing the long-term impacts of policy incentives to ensure the economic and environmental sustainability of SAF.

**Keywords:** Sustainable Aviation Fuel (SAF); Decarbonization; Life Cycle Assessment (LCA); Techno-Economic Analysis (TEA); Feedstock Availability; Greenhouse Gas (GHG) Emissions

## 1. Introduction

Sustainable Aviation Fuel (SAF) has emerged as a critical component in the global effort to decarbonize the aviation sector, which accounts for approximately 2-3% of global $CO_2$ emissions (International Air Transport Association [IATA], 2021). SAF, derived from renewable feedstocks such as waste oils, agricultural residues, and synthetic fuels, has the potential to reduce lifecycle greenhouse gas (GHG) emissions by up to 80% compared to conventional jet fuel (U.S. Department of Energy [DOE], 2023). The U.S. government has set ambitious decarbonization goals, including achieving net-zero emissions by 2050, with the aviation sector playing a pivotal role in this transition. However, producing and supplying SAF involves substantial economic and sustainability challenges, making it essential to conduct thorough Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) to ensure alignment with sustainability objectives. The production of SAF is currently hindered by high costs, limited scalability, and feedstock availability. According to a study by Elgowainy et al. (2012), the production cost of SAF ranges from 3 to 6 per gallon, significantly higher than conventional jet fuel, which averages around $2 per gallon. This cost disparity is primarily due to the complex

* Corresponding author: Irham Tanjung.

conversion processes, such as Fischer-Tropsch synthesis and hydroprocessed esters and fatty acids (HEFA), which require substantial capital investment and operational expenses. Additionally, the availability of sustainable feedstocks is constrained by competition with other industries, such as biodiesel and renewable diesel, further exacerbating supply chain challenges (Holladay et al., 2009). TEA studies highlight the need for technological advancements and policy incentives, such as tax credits and carbon pricing, to improve the economic viability of SAF production and encourage industry adoption.

From a sustainability perspective, SAF production must address environmental trade-offs, including land-use change, water consumption, and indirect emissions. LCA studies reveal that while SAF can significantly reduce GHG emissions compared to conventional jet fuel, the environmental benefits vary depending on the feedstock and production pathway. For instance, SAF derived from algae or waste oils demonstrates a lower carbon footprint than those produced from food crops, which may lead to deforestation and biodiversity loss (Staples et al., 2017). Furthermore, the energy-intensive nature of some conversion processes can offset the emissions reductions achieved by SAF. To align with U.S. decarbonization goals, it is essential to prioritize low-impact feedstocks, optimize production technologies, and integrate renewable energy sources into the supply chain. Policymakers and industry stakeholders must collaborate to establish robust sustainability criteria and certification systems to ensure the long-term environmental benefits of SAF.

The production and supply of SAF present both economic and sustainability challenges that must be addressed to achieve U.S. decarbonization goals. LCA and TEA provide valuable frameworks for evaluating the environmental and economic performance of SAF, guiding the development of cost-effective and sustainable production pathways. By leveraging technological innovation, policy support, and cross-sector collaboration, the aviation industry can overcome these challenges and accelerate the transition to a low-carbon future.

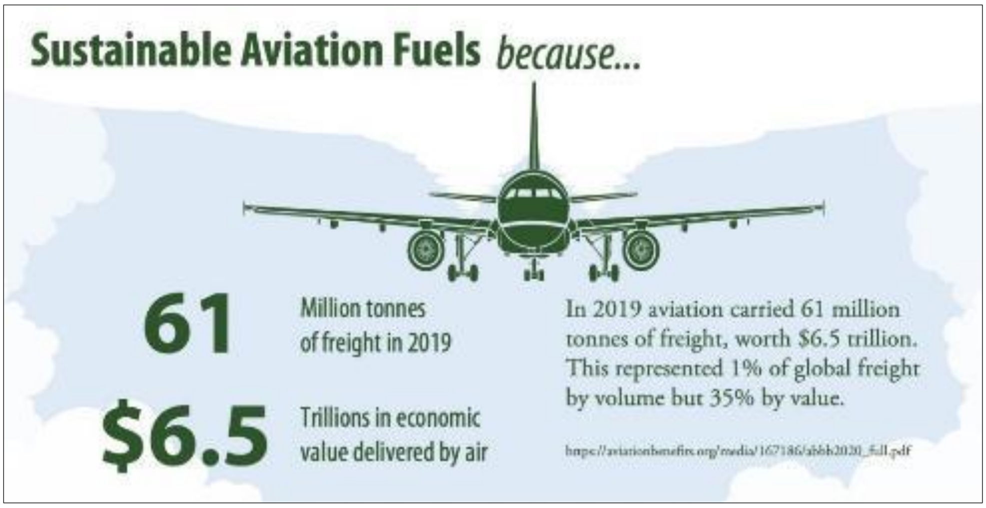


**Figure 1** The air transport sector accounts for approximately 3% of global GHG emissions, with projections indicating further growth. Reducing these emissions is essential to meeting global climate targets. SAF, which has a lower emissions intensity compared to conventional fuels, is a promising solution. However, its high cost has limited widespread adoption by making it financially challenging for many industries and stakeholders to invest in and transition to this technology. In setting, which involves purchasing emission reductions within a value chain, helps distribute the cost premium of SAF and encourages its use. Smart Freight Centre and MIT CTL have developed in setting guidelines to scale SAF adoption and advance aviation decarbonization. The framework fosters long-term collaboration across the value chain while ensuring that emission reductions are credible, properly accounted for, and aligned with international standards (Sustainable Supply Chain Lab, 2021)

### 1.1. Challenges and Importance of LCA and TEA

Sustainable Aviation Fuel (SAF) is a cornerstone of the aviation industry's efforts to reduce greenhouse gas emissions and align with U.S. decarbonization goals. Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) are indispensable tools for evaluating the environmental and economic viability of SAF production pathways. LCA provides a comprehensive analysis of the environmental impacts associated with SAF, from feedstock cultivation to fuel combustion, enabling stakeholders to identify hotspots and optimize processes for lower carbon footprints. For instance, studies have shown that SAF derived from waste feedstocks, such as municipal solid waste or agricultural residues, can achieve significant greenhouse gas reductions compared to conventional jet fuel, with some pathways achieving up to 80% lower emissions (Staples et al., 2017). Meanwhile, TEA assesses the economic feasibility of these pathways, considering capital and operational costs, feedstock availability, and market dynamics. This dual approach ensures that SAF production is not only environmentally sustainable but also economically viable, which is critical for scaling up production to meet global aviation demand.

The integration of LCA and TEA is particularly important in addressing the economic and sustainability challenges of SAF production and supply. For example, while certain feedstocks like algae or hydrogenated esters and fatty acids (HEFA) show promise in reducing emissions, their high production costs and scalability issues pose significant barriers to commercialization (Liu et al., 2021). LCA helps quantify the trade-offs between different feedstocks and conversion technologies, while TEA identifies cost-reduction opportunities, such as process optimization or policy incentives like carbon credits. Furthermore, aligning SAF production with U.S. decarbonization goals requires a holistic understanding of the entire supply chain, including feedstock logistics, energy inputs, and end-use emissions. By leveraging LCA and TEA, policymakers and industry stakeholders can make informed decisions that balance environmental benefits with economic realities, ultimately accelerating the transition to a sustainable aviation sector.


**Figure 2** The transition to sustainable aviation fuel (SAF) faces significant challenges, including high production costs, limited feedstock availability, inadequate infrastructure, and the need for international collaboration and supportive policies. High costs and uncertain demand deter investment, while competition for sustainable feedstocks and environmental concerns further complicate production. Addressing these barriers requires technological advancements, clear regulatory frameworks, and coordinated efforts among airlines, governments, and fuel suppliers to scale SAF adoption and meet aviation's sustainability goals (Greenfield, 2023)

### 1.2. Research Objectives

The production and supply of Sustainable Aviation Fuel (SAF) are critical to achieving U.S. decarbonization goals, yet they face significant economic and sustainability challenges. One major research objective is to identify the key economic barriers that hinder the scalability of SAF production. These include high production costs, limited feedstock availability, and the need for substantial capital investment in advanced biorefineries. A study by Barke et al. (2022) highlights that the cost of SAF production is currently two to four times higher than conventional jet fuel, primarily due to the high costs of feedstock processing and conversion technologies. Additionally, the variability in feedstock prices and supply chain logistics further complicates the economic viability of SAF. Addressing these challenges requires a comprehensive understanding of the cost drivers and potential pathways to reduce production costs through technological innovation and economies of scale.

From a sustainability perspective, evaluating the environmental impacts of different feedstock options is another critical research objective. Life Cycle Assessment (LCA) studies, such as those conducted by Staples et al. (2018), emphasize that the choice of feedstock significantly influences the carbon intensity and overall sustainability of SAF. For instance, waste-based feedstocks like used cooking oil and agricultural residues generally offer lower greenhouse gas (GHG) emissions compared to first-generation feedstocks like corn or sugarcane. However, the availability of these waste-based feedstocks is limited, and their collection and processing can introduce additional environmental and logistical challenges. Furthermore, indirect land-use changes (ILUC) associated with certain feedstocks can offset the carbon savings, underscoring the need for robust sustainability criteria and certification systems to ensure that SAF production aligns with decarbonization goals.

Policy and market incentives play a vital role in addressing the economic and sustainability challenges of SAF production and supply by encouraging investment, supporting innovation, and creating demand for cleaner aviation fuels. Research by Winchester et al. (2019) suggests that policy mechanisms such as carbon pricing, tax credits, and blending mandates can play a pivotal role in incentivizing SAF adoption. For example, the U.S. Renewable Fuel Standard (RFS) and the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) provide frameworks for promoting SAF use. However, the effectiveness of these policies depends on their design and implementation, including the level of financial support and the alignment with broader decarbonization strategies. A Techno-Economic Analysis (TEA) approach can help quantify the economic impacts of these policies and identify the most effective combinations of incentives to drive SAF market growth while ensuring environmental sustainability.

## 2. Literature review

### 2.1. SAF Production Pathways: Feedstock Sources

The selection of feedstock for Sustainable Aviation Fuel (SAF) production is critical to achieving both economic viability and environmental sustainability. Feedstocks such as algae, waste biomass, and plant oils have been extensively studied for their potential to reduce greenhouse gas (GHG) emissions compared to conventional jet fuels. Algae, for instance, offer high lipid content and can be cultivated on non-arable land, minimizing competition with food production (Chisti, 2007). However, the scalability and cost-effectiveness of algal biofuels remain challenging due to high cultivation and processing costs. Waste biomass, including agricultural residues and municipal solid waste, is another promising feedstock due to its low cost and abundance. According to Staples et al. (2018), waste-based feedstocks can reduce lifecycle GHG emissions by up to 80% compared to fossil fuels, but logistical challenges in collection and preprocessing can hinder their widespread adoption. Plant oils, such as those derived from camelina or jatropha, are also viable but raise concerns about land-use change and biodiversity impacts. A study by Bailis and Baka (2010) highlights the importance of sustainable sourcing practices to mitigate these risks.

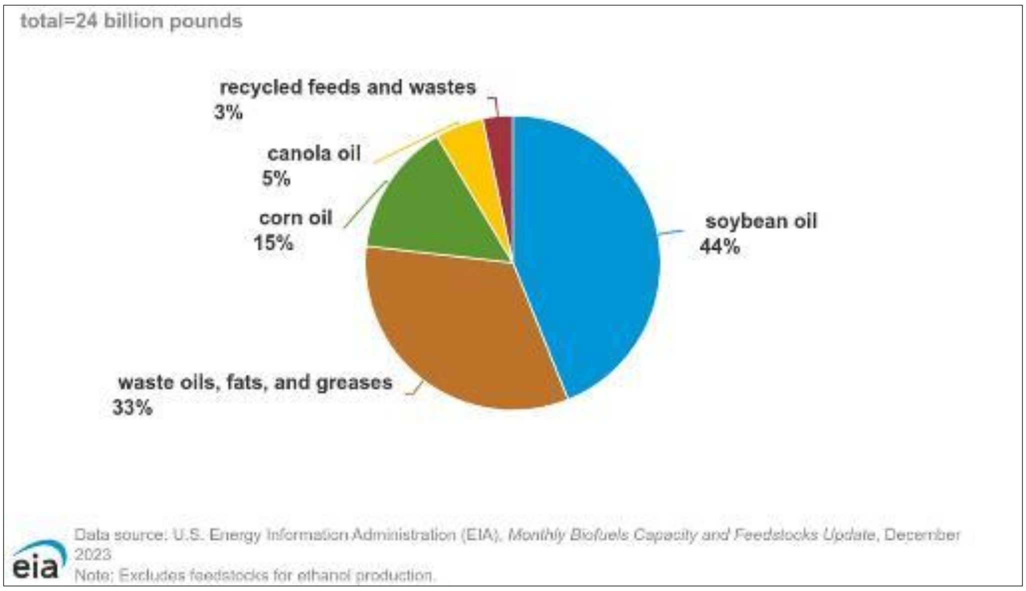


**Figure 3** In 2022, U.S. biodiesel and renewable diesel production primarily relied on soybean oil, which accounted for 44% of feedstocks, followed by corn oil (15%), waste oils, fats, and greases (33%), recycled feedstocks and wastes (3%), and canola oil (5%). Soybean oil emerged as the leading feedstock for biodiesel production (Gallucci, 2024)

### 2.2. SAF Production Pathways: Conversion Technologies

The conversion of feedstocks into SAF involves several pathways, each with distinct technical and environmental implications. The Hydro-processed Esters and Fatty Acids (HEFA) pathway is the most commercially mature, utilizing hydrogenation to convert fats, oils, and greases into hydrocarbons suitable for aviation. HEFA is currently the dominant SAF production method, accounting for over 90% of global SAF supply (IATA, 2022). However, its reliance on limited feedstock availability and high hydrogen demand poses sustainability challenges. The Alcohol-to-Jet (ATJ) pathway, which converts alcohols like ethanol or butanol into jet fuel, offers flexibility in feedstock selection, including lignocellulosic biomass and waste streams. According to Kauffman et al. (2011), ATJ can achieve significant GHG reductions but requires further technological advancements to improve energy efficiency and reduce costs. The Power-to-Liquid (PtL) pathway, which synthesizes liquid fuels from renewable electricity, water, and $CO_2$, is considered a long-term solution for decarbonizing aviation. A study by Schmidt et al. (2016) estimates that PtL could achieve near-zero lifecycle emissions if powered by renewable energy, but high capital costs and energy requirements remain significant barriers to commercialization.

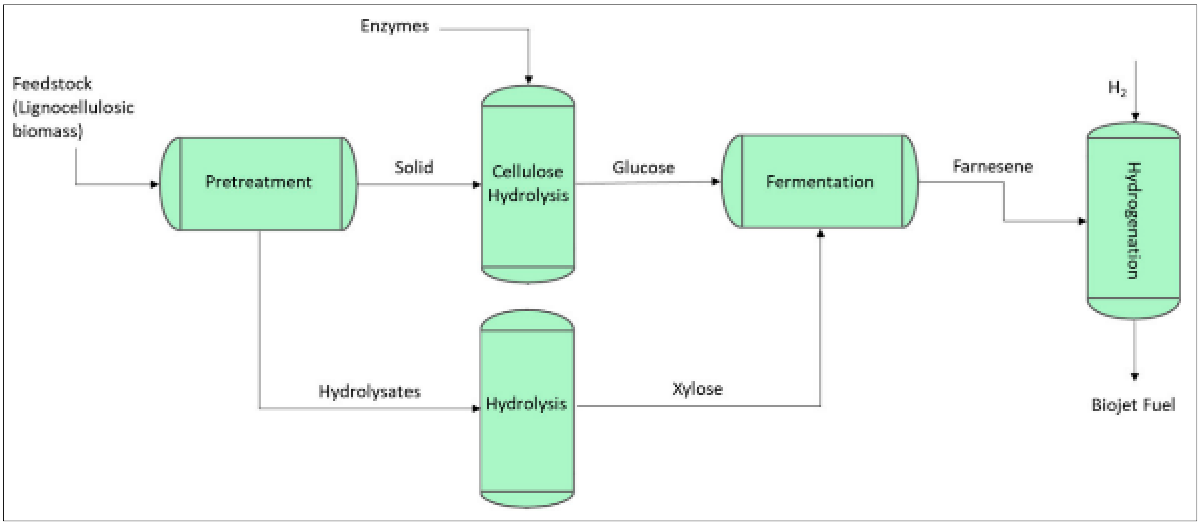


**Figure 4** Methanol, ethanol, butanol, and long-chain fatty alcohols have emerged as promising feedstocks for biojet fuel production, thanks to their widespread availability, sustainable origins, and compatibility with current fuel infrastructure. These alcohols, sourced from biomass, agricultural waste, or dedicated energy crops, undergo processing via the Alcohol-to-Jet (ATJ) pathway. This method involves dehydration, oligomerization, and hydrogenation to transform the alcohol into hydrocarbons suitable for aviation fuel. The resulting products, which include alkanes, cycloalkanes, and aromatics, align with the carbon specifications of traditional jet fuel, making them a viable component for sustainable aviation fuel blends (Peters et al., 2023)

### 2.3. SAF Production Pathways: Environmental Impacts

Life Cycle Assessment (LCA) studies are essential for evaluating the environmental performance of SAF production pathways. HEFA, while commercially viable, has been criticized for its reliance on feedstocks that may indirectly contribute to deforestation and land-use change (Searchinger et al., 2008). In contrast, waste-based feedstocks and PtL pathways demonstrate superior environmental performance, with potential GHG reductions exceeding 90% compared to conventional jet fuel (De Jong et al., 2017). However, the environmental benefits of these pathways are highly dependent on factors such as feedstock sourcing, energy inputs, and process efficiency. For instance, the sustainability of PtL is contingent on the availability of low-carbon electricity, while waste-based pathways must address emissions from feedstock collection and transportation. A comprehensive LCA framework that accounts for these variables is crucial for accurately assessing the environmental impacts of SAF production.

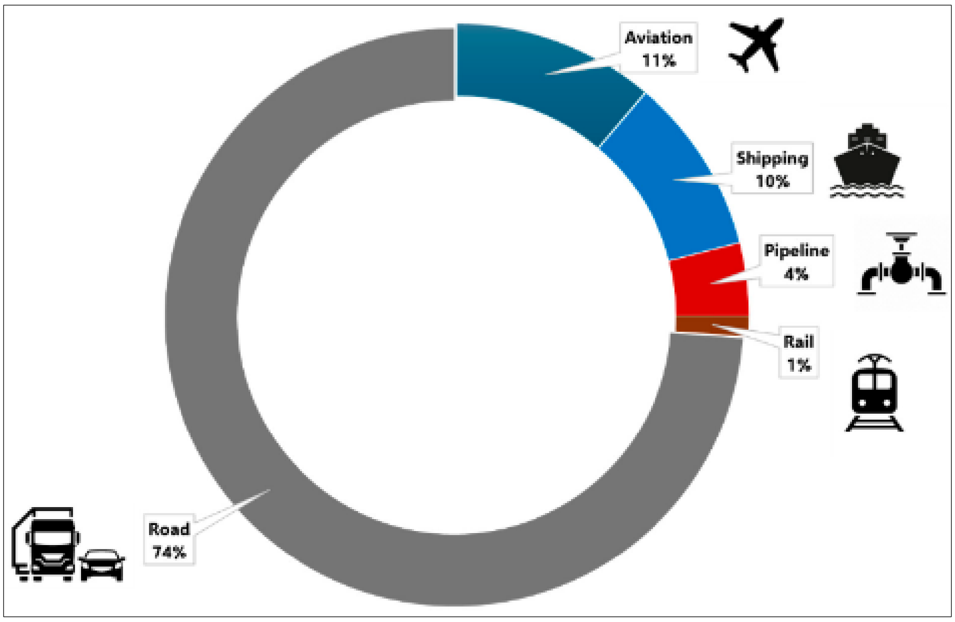


**Figure 5** Global transportation accounts for approximately 20% of total CO2 emissions, with road vehicles—including passenger cars and trucks—being the largest contributor at roughly three-quarters of the sector's emissions. Shipping and aviation also play significant roles, with shipping being carbon-intensive and aviation emissions rebounding to nearly 90% of pre-pandemic levels as travel demand recovered. Rail, pipelines, and other modes contribute less, but overall global transportation emissions have risen by nearly 40% since 2000, reaching almost 8 billion metric tons of CO2 in 2022, with the United States leading as the largest emitter (D'Ascenzo et al., 2024)

### 2.4. SAF Production Pathways: Economic and Business Perspectives

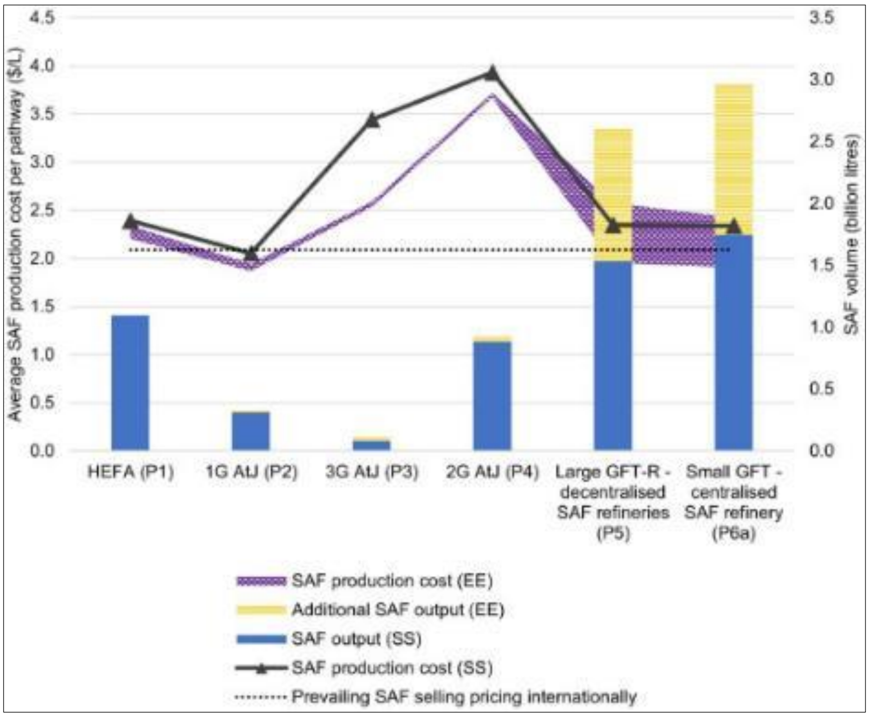


**Figure 6** The production costs and total output of sustainable aviation fuel (SAF) across various pathways. The pathways include P1 (Pathway 1), P2 (Pathway 2), P3 (Pathway 3), P4 (Pathway 4), P5 (Pathway 5), and P6a (Pathway 6a), alongside key technologies such as HEFA (hydroprocessed esters and fatty acids), AtJ (alcohol-to-jet), GFT (gasification and Fischer-Tropsch), and GFT-R (gasification, Fischer-Tropsch, and refining). The analysis also considers generational classifications (1G = first generation, 2G = second generation, 3G = third generation) and scenarios like SS (energy self-sufficiency) and EE (external energy) (Chireshe et al., 2025)

Techno-Economic Analysis (TEA) provides insights into the cost competitiveness and scalability of SAF production pathways. HEFA currently has the lowest production cost among SAF technologies, ranging from 0.80 *to* 1.50 per liter, but its reliance on finite feedstock limits long-term scalability (Pearlson et al., 2013). ATJ and PtL pathways, while more expensive, offer greater potential for cost reduction through technological innovation and economies of scale. A study by Eswaran et al. (2021) suggests that policy incentives, such as carbon pricing and renewable fuel mandates, are critical for bridging the cost gap between SAF and conventional jet fuel. From a business perspective, the integration of SAF into existing supply chains requires collaboration among airlines, fuel producers, and policymakers. Corporate sustainability goals, such as those outlined by the International Air Transport Association (IATA) and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), are driving demand for SAF, but achieving U.S. decarbonization goals will require significant investment in infrastructure and technology development.

### 2.5. SAF Production Pathways: LCA Studies on SAF

Sustainable Aviation Fuel (SAF) production and supply present significant economic and sustainability challenges, particularly in aligning with U.S. decarbonization goals. Life Cycle Assessment (LCA) studies on SAF have been instrumental in evaluating the environmental impacts of various production pathways. These studies typically focus on key impact categories such as greenhouse gas (GHG) emissions, land use change, water consumption, and energy use. For instance, Chireshe et al. (2025) critically evaluates a comprehensive LCA of SAF derived from different feedstocks, highlighting that feedstock selection significantly influences GHG emissions and land use impacts. Their findings emphasize that while some pathways, such as those using agricultural residues, show promise in reducing lifecycle emissions, others, like those relying on food-based feedstocks, could result in indirect land use change (ILUC) and increased carbon footprints. Sensitivity analyses in these studies often reveal that the cultivation, harvesting, and processing stages are the most impactful, underscoring the need for sustainable feedstock sourcing and efficient conversion technologies to achieve meaningful decarbonization.

From a Techno-Economic Analysis (TEA) and business perspective, the scalability and cost-competitiveness of SAF remain critical barriers. According to a study by Shahriar & Khanal (2022), the production costs of SAF are currently higher than those of conventional jet fuel, primarily due to the high capital and operational expenses associated with advanced biofuel technologies. However, economies of scale and technological advancements, such as improved catalytic processes and co-product utilization, could reduce costs over time. Additionally, policy incentives, such as the U.S. Renewable Fuel Standard (RFS) and the Inflation Reduction Act (IRA), play a pivotal role in bridging the economic gap. Business models that integrate SAF production with existing petroleum refineries or biorefineries have shown potential for cost savings and reduced environmental impacts, as highlighted by Dineshkumar and Sen (2020). Aligning SAF production with U.S. decarbonization goals requires a holistic approach that combines robust LCA methodologies, innovative TEA frameworks, and supportive policy measures to address both environmental and economic challenges.

### 2.6. SAF Production Pathways: TEA Studies on SAF

The production and supply of Sustainable Aviation Fuel (SAF) present significant economic challenges that must be addressed to align with U.S. decarbonization goals. Techno-Economic Analysis (TEA) studies highlight that feedstock costs are one of the most substantial cost drivers in SAF production, often accounting for 50-70% of the total production cost (Watson et al., 2024). Feedstock availability and price volatility, particularly for bio-based sources like waste oils, agricultural residues, and algae, directly impact the economic feasibility of SAF. Additionally, capital investment for biorefineries and advanced conversion technologies, such as Fischer-Tropsch synthesis and hydroprocessed esters and fatty acids (HEFA), requires significant upfront expenditure, often exceeding $1 billion for large-scale facilities (Shahriar & Khanal, 2022). Operating expenses, including energy consumption, labor, and maintenance, further contribute to the high production costs. However, policy incentives such as tax credits, carbon pricing, and renewable fuel standards (RFS) can play a pivotal role in reducing the financial burden and improving the competitiveness of SAF against conventional jet fuel (Lim et al., 2023).

From an economic feasibility perspective, TEA studies estimate the minimum selling price (MSP) of SAF to range between 3.50 and 6.00 per gallon, depending on the feedstock and conversion pathway (Rojas-Michaga et al., 2023). Sensitivity analyses reveal that feedstock cost, conversion efficiency, and policy support are the most critical parameters influencing MSP. For instance, a 20% reduction in feedstock cost can lower the MSP by approximately 0.50 per gallon, *while a* 100.30 per gallon (Bhatt et al., 2023). Furthermore, economies of scale and technological advancements are essential to achieving cost parity with conventional jet fuel, which currently averages around $2.50 per gallon. Despite these challenges, the growing demand for decarbonization in the aviation sector and the potential for carbon credit and corporate sustainability commitments are driving investment and innovation in SAF production. Aligning TEA findings with life cycle assessment (LCA) and business strategies will be crucial to ensuring the long-term economic and environmental sustainability of SAF (Wang & Yu, 2024).

## 3. Key Challenges in SAF Production and Supply

### 3.1. Feedstock Availability and Sustainability

Sustainable Aviation Fuel (SAF) production and supply face significant economic and sustainability challenges, particularly in aligning with U.S. decarbonization goals. A major concern is the availability and sustainability of suitable feedstocks. The production of SAF relies heavily on biomass feedstocks, such as agricultural residues, algae, and waste oils, which must be sourced sustainably to avoid adverse environmental impacts. However, the competition for land use between food crops and energy crops poses a critical challenge. For instance, diverting agricultural land for feedstock production can exacerbate food insecurity and increase food prices, creating a trade-off between energy sustainability and food security (Searchinger et al., 2008). Additionally, the potential for indirect land use change (ILUC)—where land previously used for food production is converted to grow biofuel feedstocks, leading to deforestation or the conversion of natural habitats—adds an additional layer of complexity to the sustainability of SAF production (Fargione et al., 2008). These issues highlight the need for robust sustainable sourcing practices to ensure that biomass feedstock is procured without compromising ecosystems or food systems.

From a Life Cycle Assessment (LCA) perspective, the environmental benefits of SAF depend heavily on the feedstock's carbon footprint and the efficiency of the production process. While SAF has the potential to reduce greenhouse gas (GHG) emissions by up to 80% compared to conventional jet fuel, this reduction is contingent on the sustainability of the feedstock supply chain (Staples et al., 2017). For example, feedstocks like waste oils and agricultural residues generally have lower ILUC risks and GHG emissions compared to purpose-grown energy crops. However, the scalability of these feedstocks is limited by their availability and collection logistics. Furthermore, the energy-intensive processes involved in converting biomass to SAF, such as hydroprocessing or Fischer-Tropsch synthesis, can offset some of the environmental benefits if not powered by renewable energy (De Jong et al., 2017). Thus, LCA studies emphasize the importance of integrating renewable energy into SAF production facilities to maximize decarbonization potential.

From a Techno-Economic Analysis (TEA) standpoint, the high production costs of SAF remain a significant barrier to widespread adoption. Current SAF production costs are substantially higher than those of conventional jet fuel, primarily due to the high capital and operational expenses associated with advanced biofuel technologies (Joodi et al., 2024). For instance, the Fischer-Tropsch process, which converts biomass-derived syngas into liquid hydrocarbons, requires significant upfront investment and operational expertise. Additionally, the variability in feedstock prices and availability further exacerbates economic uncertainties. To address these challenges, policymakers and industry stakeholders are exploring financial incentives, such as tax credits and subsidies, to make SAF more competitive with fossil-based jet fuel (IEA, 2021). However, achieving cost parity will require technological advancements, economies of scale, and continued policy support.

From a business perspective, the SAF market faces challenges related to supply chain integration, regulatory compliance, and market demand. Airlines and fuel producers must navigate complex regulatory frameworks, such as the U.S. Renewable Fuel Standard (RFS) and the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which mandate specific GHG reduction targets (ICAO, 2021). Additionally, the lack of infrastructure for SAF production, storage, and distribution poses logistical challenges. For example, SAF must meet stringent quality standards to ensure compatibility with existing aircraft engines, which limit the types of feedstocks and conversion technologies that can be used (Chiaramonti, 2019). Despite these hurdles, the growing demand for sustainable aviation solutions, driven by corporate sustainability commitments and consumer preferences, presents a significant opportunity for SAF market expansion. Collaborative efforts among governments, industries, and research institutions will be crucial to overcoming these challenges and aligning SAF production with U.S. decarbonization goals.

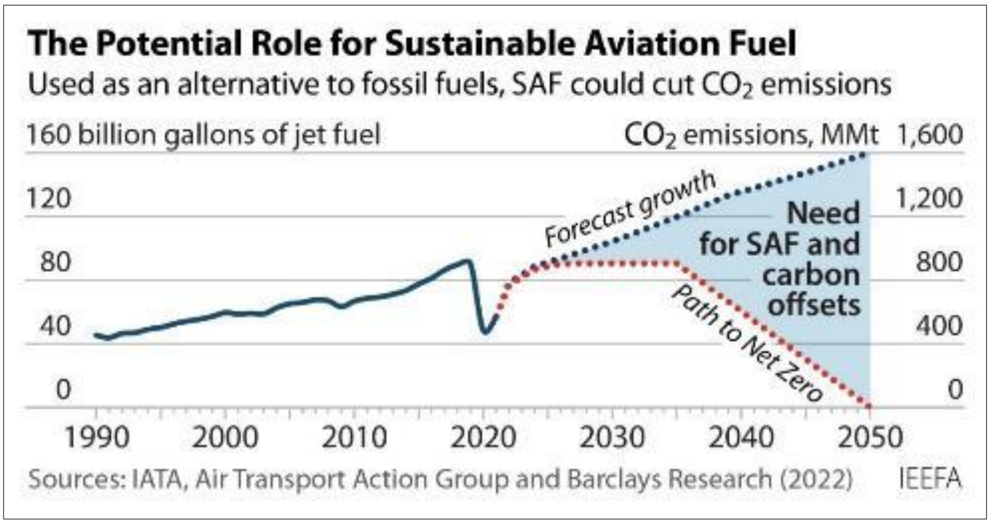


**Figure 7** The aviation industry faces significant challenges in reducing its carbon footprint, but sustainable aviation fuel (SAF) offers a promising alternative to fossil fuels if cost barriers and sustainability concerns are addressed. Derived from feedstocks like biomass or waste oils, SAF can substantially lower life cycle greenhouse gas emissions compared to conventional jet fuel, helping the industry meet near-term targets. However, challenges such as deforestation risks, water usage, and high production costs must be resolved through sustainable practices, innovation, and investment to ensure SAF's viability and widespread adoption (Sinha, 2024)

### 3.2. Production Costs and Economics

The production of Sustainable Aviation Fuel (SAF) faces significant economic challenges, primarily due to the high capital investment required for establishing SAF refineries. According to a study by Wang et al. (2019), the capital costs for SAF production facilities are substantially higher than those for conventional fossil fuel refineries, primarily due to the need for advanced technologies such as Fischer-Tropsch synthesis or hydroprocessed esters and fatty acids (HEFA) processes. These technologies are essential for converting biomass, waste oils, or other renewable feedstocks into SAF, but they require specialized infrastructure and significant upfront investment. This financial barrier often deters investors and limits the rapid scale-up of SAF production, which is critical for meeting U.S. decarbonization goals (Wang et al., 2019).

Scale-up challenges and achieving economies of scale further complicate the economic viability of SAF production. De Jong et al. (2017) highlights that SAF production is still in its nascent stages, with most facilities operating at pilot or demonstration scales. Scaling up to commercial levels is hindered by feedstock availability, technological uncertainties, and the need for significant infrastructure upgrades. For instance, the production of SAF from lignocellulosic biomass requires extensive supply chain logistics to ensure a consistent and cost-effective feedstock supply. Economies of scale could reduce production costs over time but achieving this requires substantial investment and coordination among stakeholders, including policymakers, industry players, and researchers (De Jong et al., 2017).

Policy mechanisms, such as carbon credit and tax incentives, play a crucial role in influencing SAF production costs and economic feasibility. Kousoulidou and Lonza (2016) emphasize that carbon pricing and renewable fuel credits can significantly offset the high production costs of SAF, making it more competitive with conventional jet fuel. For example, the U.S. Renewable Fuel Standard (RFS) and the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) provide financial incentives for SAF producers. However, the effectiveness of these policies depends on their stability and long-term implementation. Without consistent policy support, the economic risks associated with SAF production may discourage investment, thereby slowing progress toward decarbonization targets (Kousoulidou & Lonza, 2016).

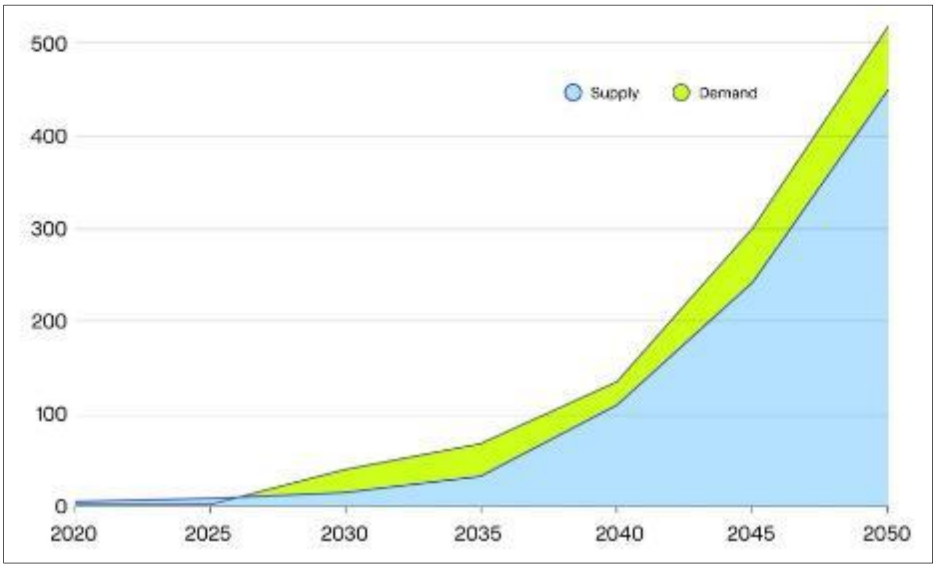


**Figure 8** Global predicted SAF demand from 2022 to 2050 (in millions of tonnes) shows rapid growth, with production expected to meet demand until 2027. However, a projected 26.2% compound annual growth rate (CAGR) through 2050 is likely to result in a significant supply-demand gap, surpassing 25% by 2040. This surge in SAF demand, driven by policy targets and outpacing overall jet fuel demand, may be influenced by factors such as rising travel costs and slower passenger growth, estimated at 3% (TOPSOE, 2025)

### 3.3. Infrastructure and Logistics

The production and supply of Sustainable Aviation Fuel (SAF) present significant economic and sustainability challenges, particularly in aligning with U.S. decarbonization goals. A critical issue is the need for dedicated storage and distribution networks for SAF, as its chemical properties often differ from conventional jet fuel. SAF necessitates dedicated infrastructure to avoid contamination and ensure compatibility with aircraft engines, which can be expensive to build and sustain. According to research conducted by Staples et al. (2018), the integration of SAF into existing aviation fuel infrastructure is complex, as it necessitates upgrades to storage tanks, pipelines, and refueling systems to handle new fuel blends. These logistical challenges are compounded by the fragmented nature of the aviation fuel supply chain, which involves multiple stakeholders, including fuel producers, distributors, and airlines. The economic burden of building new infrastructure or retrofitting existing systems can deter investment, particularly in regions with limited demand for SAF (Staples et al., 2017).

From a sustainability perspective, the environmental benefits of SAF must be weighed against the energy and resource inputs required for its production and distribution. The Life Cycle Assessment (LCA) studies highlight that while SAF can significantly reduce greenhouse gas emissions compared to conventional jet fuel, the overall sustainability depends on the feedstock and production pathways used. For instance, Han et al. (2020) emphasize that the carbon intensity of SAF varies widely depending on factors such as land-use change, feedstock cultivation, and processing methods. Additionally, the integration of SAF into existing infrastructure must be carefully managed to avoid unintended environmental impacts, such as increased energy consumption or emissions during transportation and storage. Techno-Economic Analysis (TEA) further underscores the need for cost-effective solutions to scale up SAF production while maintaining environmental integrity. Without significant policy support and investment in infrastructure, the aviation industry may struggle to meet decarbonization targets, highlighting the importance of aligning LCA, TEA, and business perspectives to address these challenges (Han et al., 2020).

### 3.4. Technology Development

The production and supply of Sustainable Aviation Fuel (SAF) present significant economic and sustainability challenges, particularly in aligning with U.S. decarbonization goals. Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) are critical tools for evaluating the environmental and economic viability of SAF production pathways. According to Hannula et al. (2020), the high production costs of SAF, driven by feedstock availability and conversion technology inefficiencies, remain a major barrier to widespread adoption. Additionally, certain conversion pathways, such as hydroprocessed esters and fatty acids (HEFA), while commercially viable, may have unintended environmental consequences, including land-use change and biodiversity loss. These challenges highlight the need for improved efficiency and cost reduction in SAF production technologies to ensure scalability and sustainability (Alic, 2016).

Furthermore, Bauen et al. (2020) emphasize that aligning SAF production with decarbonization goals requires a holistic approach, integrating LCA and TEA to identify pathways that minimize greenhouse gas (GHG) emissions while maintaining economic feasibility.

From a business perspective, the development of SAF technologies must address both economic and environmental trade-offs to achieve long-term sustainability. De Jong et al. (2017) note that the high capital and operational expenditures associated with advanced biofuel production, such as Fischer-Tropsch synthesis and alcohol-to-jet pathways, pose significant financial risks for investors. However, technological advancements, such as catalyst optimization and process intensification, offer promising avenues for reducing costs and improving efficiency (De Jong et al., 2017). Moreover, ICAO (2021) highlights the importance of policy support and market incentives to bridge the cost gap between SAF and conventional jet fuel. Addressing potential negative environmental impacts, such as water usage and feedstock competition, is equally critical to ensure the sustainability of SAF production. By integrating LCA, TEA, and business perspectives, stakeholders can develop strategies that align SAF production with U.S. decarbonization goals while fostering economic viability and environmental stewardship (ICAO, 2021).

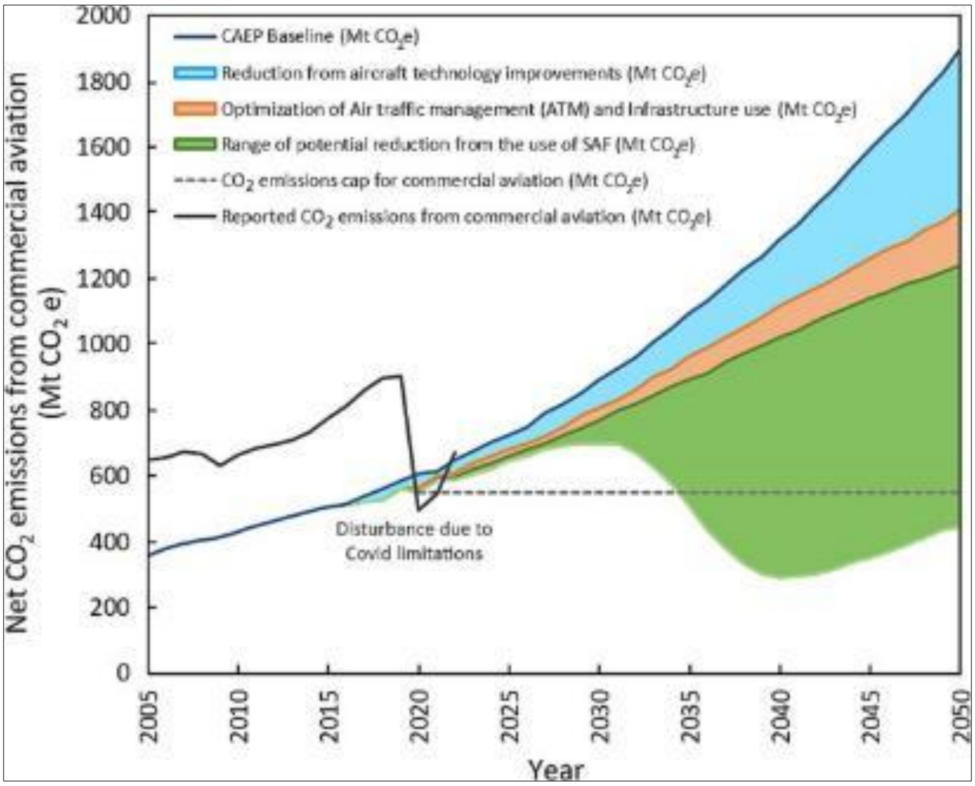


**Figure 9** Net emissions from both commercial aviation and international aviation are depicted in the analysis. The colored areas illustrate the estimated reduction in $CO_2$ emissions specifically attributed to international aviation, which primarily includes long-haul flights. These reductions reflect efforts and advancements in fuel efficiency, operational improvements, and the adoption of sustainable aviation fuels (SAFs) within the sector. The data highlights the progress made in mitigating the environmental impact of aviation, particularly in the context of global efforts to address climate change (Almena et al., 2024)

## 4. Aligning SAF Production with U.S. Decarbonization Goals

### 4.1. Policy Framework Analysis

Sustainable Aviation Fuel (SAF) production and supply present significant economic and sustainability challenges, particularly in aligning with U.S. decarbonization goals. Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) are critical tools for evaluating the environmental and economic viability of SAF pathways. According to Staples et al. (2017), LCA studies reveal that SAF derived from waste feedstocks, such as agricultural residues and municipal solid waste, can reduce greenhouse gas (GHG) emissions by up to 80% compared to conventional jet fuel. However, the economic feasibility of these pathways often hinges on policy support and economies of scale. TEA studies highlight that high capital and operational costs, coupled with uncertain feedstock availability, pose significant barriers to scaling SAF production (Watson et al., 2024). Addressing these challenges requires a robust policy framework that incentivizes investment in SAF technologies while ensuring sustainability criteria are met.

The existing U.S. policy framework provides foundational support for SAF production, primarily through tax credits and grants. The Inflation Reduction Act (IRA) of 2022, for instance, includes tax incentives for low-carbon fuels, which can significantly reduce the cost gap between SAF and conventional jet fuel (Congress.gov, 2022). Additionally, the Renewable Fuel Standard (RFS) mandates the blending of renewable fuels into the transportation fuel supply, creating a market for SAF. However, these policies alone may not be sufficient to achieve the ambitious decarbonization targets set by the U.S. aviation sector. A study by Grobler et al. (2019) emphasizes the need for complementary policies, such as carbon pricing or low-carbon fuel standards, to further incentivize SAF adoption and ensure long-term market stability. These strategies could help close the economic gap and speed up the shift toward sustainable aviation.

Feedstock selection is a critical factor in aligning SAF production with sustainability goals. Policies must address the trade-offs between feedstock availability, environmental impact, and economic viability. For example, while first-generation feedstocks like vegetable oils are readily available, their use raises concerns about land-use change and competition with food production (Change, 2008). In contrast, advanced feedstocks, such as algae and waste oils, offer higher sustainability benefits but face technological and logistical challenges. A study by Pearlson et al. (2013) suggests that policy frameworks should prioritize feedstocks with low carbon intensity and minimal environmental impact, supported by robust sustainability certification systems. This approach would ensure that SAF production contributes to decarbonization without unintended ecological consequences.

From a business perspective, aligning SAF production with U.S. decarbonization goals requires a collaborative approach involving policymakers, industry stakeholders, and researchers. Business models that integrate vertical supply chains, such as partnerships between feedstock suppliers, fuel producers, and airlines, can enhance economic viability and reduce risks (de Jong et al., 2017). Furthermore, public-private partnerships and government-backed loan guarantees can mitigate the financial risks associated with scaling SAF technologies. A report by the International Air Transport Association (IATA, 2021) underscores the importance of aligning policy incentives with industry needs to create a sustainable and economically viable SAF market. By addressing these challenges through a combination of policy innovation, technological advancement, and stakeholder collaboration, the U.S. can achieve its decarbonization goals while fostering a resilient SAF industry.

### 4.2. Industry Partnerships and Collaboration:

The production and supply of Sustainable Aviation Fuel (SAF) present significant economic and sustainability challenges that must be addressed to align with U.S. decarbonization goals. Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) reveal that SAF production pathways, such as hydroprocessed esters and fatty acids (HEFA) and power-to-liquid (PtL) technologies, often face high capital costs, feedstock availability constraints, and energy-intensive processes (De Jong et al., 2017; Fasihi et al., 2016). These challenges are further compounded by the need to ensure that SAF achieves substantial greenhouse gas (GHG) reductions compared to conventional jet fuel, as mandated by international and national sustainability criteria. For instance, the U.S. Renewable Fuel Standard (RFS) and the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) set stringent benchmarks for SAF adoption (ICAO, 2021; U.S. EPA, 2022). To overcome these barriers, industry partnerships and collaboration are critical. Airlines, fuel producers, and government agencies must work together to scale SAF production, reduce costs, and ensure a reliable supply chain. For example, airlines like United Airlines and Delta have partnered with SAF producers such as Neste and Gevo to secure long-term offtake agreements, while government incentives like the U.S. Inflation Reduction Act (IRA) provide tax credits to lower the cost gap between SAF and conventional jet fuel (IATA, 2023; DOE, 2022).

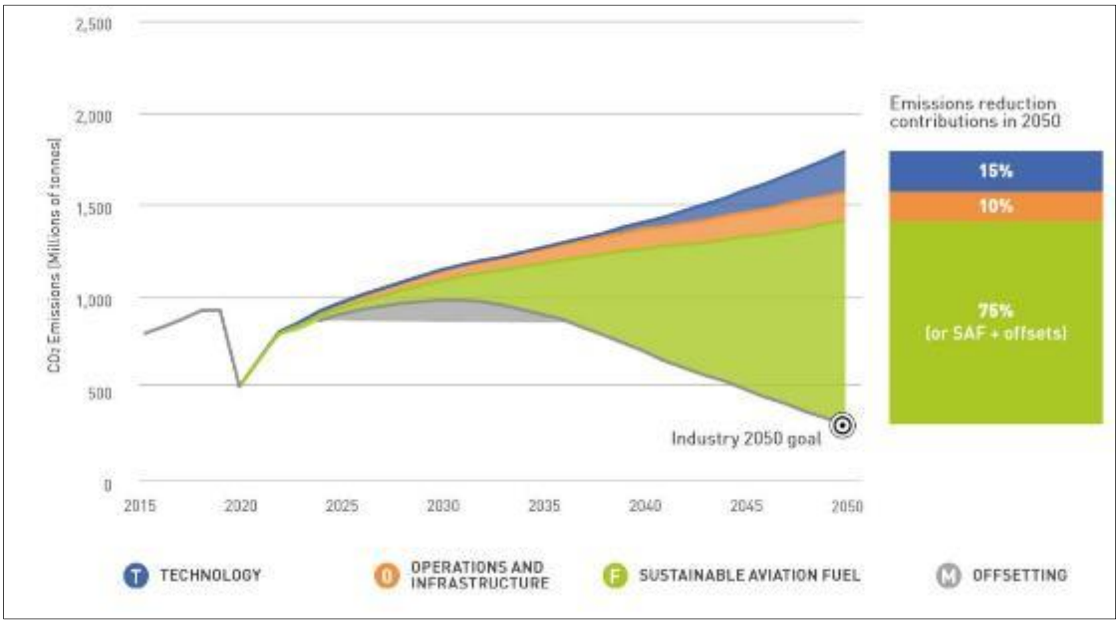


**Figure 10** The "aggressive deployment of SAF" scenario outlined in the Waypoint 2050 report demonstrates that achieving carbon neutrality in aviation is possible by around 2060. Additionally, various aviation stakeholders, such as passenger airlines and cargo operators, have publicly committed to reducing their carbon footprint with comparable levels of ambition, emphasizing the use of sustainable aviation fuel (SAF) as a key strategy (European Commission, 2021)

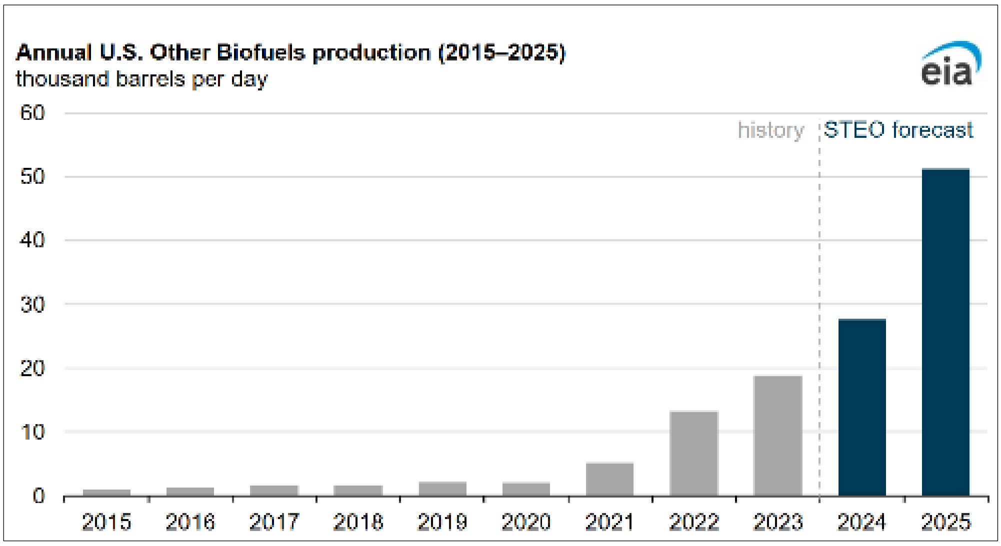


**Figure 11** According to the U.S. Energy Information Administration's *Short-Term Energy Outlook (STEO)* from July 2024 and the U.S. Environmental Protection Agency's *Moderated Transaction System (EMTS)*, data prior to 2021 is sourced from EMTS. The "Other Biofuels" category includes a range of alternative fuels such as sustainable aviation fuel (SAF), renewable heating oil, renewable naphtha, renewable propane, renewable gasoline, and additional innovative biofuels that are at different stages of research, development, and market adoption (Troderman, 2024)

From a business perspective, collaboration opportunities in research and development (R&D), technology transfer, and market access are essential to accelerate SAF deployment. Public-private partnerships, such as the U.S. Department of Energy's (DOE) Bioenergy Technologies Office (BETO) initiatives, have funded R&D projects to advance SAF technologies and improve feedstock logistics (DOE, 2021). Additionally, technology transfer between academia, national laboratories, and industry can help commercialize emerging SAF pathways, such as gasification-Fischer-Tropsch synthesis and algae-based biofuels (Li, et al., 2015). Market access can be enhanced through policy frameworks that incentivize SAF blending mandates and create stable demand signals for investors. For instance, the European Union's ReFuelEU Aviation proposal mandates a minimum share of SAF in aviation fuel, providing a model for U.S.

policymakers (Iniative, 2022). By fostering collaboration across the value chain, stakeholders can address the economic and sustainability challenges of SAF production, ensuring alignment with U.S. decarbonization goals and supporting the aviation industry’s transition to net-zero emissions.

## 5. Conclusion and Future Research Directions

### 5.1. Key Takeaways

The production and supply of Sustainable Aviation Fuel (SAF) present significant economic and sustainability challenges that must be addressed to align with U.S. decarbonization goals. Key challenges include high production costs, limited feedstock availability, and the need for advanced conversion technologies to ensure scalability and environmental benefits. Life Cycle Assessment (LCA) studies highlight the importance of reducing greenhouse gas (GHG) emissions across the entire supply chain, while Techno-Economic Analysis (TEA) underscores the financial barriers to large-scale SAF deployment, such as capital-intensive infrastructure and uncertain market demand (Osman et al., 2024; DOE, 2023). However, opportunities exist in leveraging policy incentives, such as the Inflation Reduction Act (IRA), and fostering public-private partnerships to drive investment in SAF technologies. Future research should focus on optimizing feedstock sourcing, improving conversion efficiencies, and integrating SAF production with renewable energy systems to enhance sustainability and economic viability (Chiaramonti, 2019; IEA, 2023). Addressing these challenges and capitalizing on emerging opportunities will be critical for achieving the U.S. aviation sector's decarbonization targets.

### 5.2. Research gaps

The production and supply of Sustainable Aviation Fuel (SAF) face significant economic and sustainability challenges that must be overcome to meet U.S. decarbonization goals. Key barriers identified through Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) include high production costs, limited feedstock availability, and the need for scalable technologies. From a business perspective, policy support and market incentives are critical to bridging the cost gap between SAF and conventional jet fuels. Despite advancements, research gaps persist in areas such as advanced feedstock technologies (e.g., algae and waste-derived feedstocks), lifecycle cost optimization, and comprehensive policy impact assessments to ensure both economic viability and environmental benefits.

Future research should prioritize multidisciplinary approaches to address these challenges. Key focus areas include

- Developing advanced feedstock technologies to diversify and expand feedstock availability.
- Enhancing production efficiency to lower costs and increase scalability.
- Conducting comprehensive policy impact assessments to align economic incentives with sustainability goals. By addressing these gaps, the aviation sector can achieve its decarbonization targets while fostering a sustainable and economically feasible SAF supply chain.

### 5.3. Recommendations for Policy and Industry

The production and supply of Sustainable Aviation Fuel (SAF) face significant economic and sustainability challenges that must be overcome to meet U.S. decarbonization goals. Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) highlight SAF's potential for substantial greenhouse gas (GHG) reductions compared to conventional jet fuel. Nevertheless, elevated production costs, constrained feedstock supply, and challenges in scaling up continue to pose significant obstacles. From a business perspective, inconsistent policy support and market incentives further hinder investment in SAF infrastructure. To accelerate adoption, policymakers should prioritize

- Implementing robust carbon pricing mechanisms, tax credits, and blending mandates to create a stable market environment.
- Encouraging industry collaboration to optimize feedstock supply chains, invest in advanced conversion technologies, and scale up production facilities.

Future research should focus on emerging pathways like power-to-liquid (PtL) and algae-based SAF, which offer higher sustainability and scalability. Additionally, integrating circular economy principles and leveraging digital tools for supply chain optimization could enhance SAF's economic viability and environmental performance. By addressing these challenges through coordinated policy, industry innovation, and continued research, the U.S. aviation sector can achieve its decarbonization targets while fostering a sustainable and resilient SAF market.

## Compliance with ethical standards

*Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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