
Sustainable Aviation Fuel and Its Role in Green Aviation: A Survey

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Abstract

This survey paper provides a comprehensive analysis of Sustainable Aviation Fuel (SAF) as a critical measure for reducing the aviation industry's environmental impact. It evaluates the progress and challenges in the commercialization of biojet fuels, exploring technological advancements and policy frameworks essential for SAF adoption. The survey highlights the potential of hydrogen and Power-to-Liquids (PtL) as alternative fuels, emphasizing the need for carbon-neutral solutions in aviation amidst escalating climate concerns. By examining airport roles in SAF uptake and addressing knowledge gaps in SAF implementation, the paper offers insights into biojet fuel development, technologies, and policies promoting SAF adoption. It evaluates SAF alternatives from social and business perspectives, focusing on carbon mitigation potential and investment costs. The survey also discusses aviation's environmental impact, including emissions and ecological footprints, and assesses green aviation technologies to minimize these effects. The regulatory framework, particularly SAF quotas, is analyzed, with an emphasis on international policies promoting SAF use. Finally, the paper explores social welfare and community impacts, underscoring public perception and stakeholder engagement in advancing sustainable aviation practices. The survey concludes with future research directions, proposing innovative solutions like energy beaming from solar farms to enhance aviation sustainability.

1 Introduction

1.1 Objectives and Scope of the Survey

This survey evaluates the progress and challenges in the commercialization of Sustainable Aviation Fuels (SAF), with a focus on technological advancements in this sector [1]. It aims to analyze SAF as a crucial measure for mitigating the aviation industry's climate impact, addressing both technological and policy dimensions essential for its adoption. By examining hydrogen and Power-to-Liquids (PtL) as sustainable alternatives, the survey underscores the urgent need for carbon-neutral solutions in aviation amid escalating concerns regarding global warming and climate change. Additionally, it explores the role of airports in facilitating SAF uptake in line with initiatives such as ReFuelEU, while addressing knowledge gaps related to airport involvement in SAF implementation [2]. The survey also provides insights into the current state of biojet fuel development, the technologies involved, and the policies promoting SAF adoption [3]. By evaluating the attractiveness of various SAF alternatives from social and business perspectives, it ensures a comprehensive analysis of their carbon mitigation potential and associated investment costs [4]. Ultimately, the survey contributes to the discourse on aviation decarbonization and proposes innovative solutions, including energy beaming from solar farms, to enhance the sustainability of the aviation industry [5].

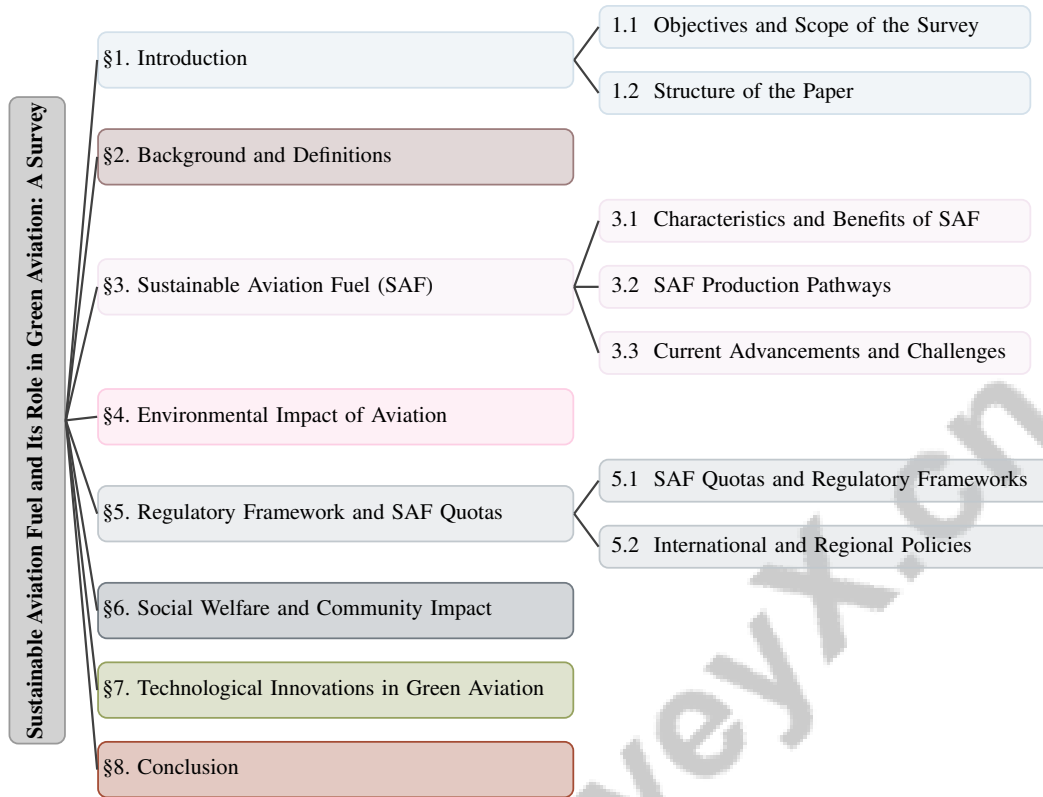


Figure 1: chapter structure

1.2 Structure of the Paper

The paper is structured to provide a thorough exploration of Sustainable Aviation Fuel (SAF) and its critical role in promoting green aviation. It begins with an introduction that outlines the objectives and scope, establishing a foundational understanding of key terms such as SAF, sulfur dioxide, SAF quotas, and green aviation [3].

Subsequently, the paper discusses the characteristics and benefits of SAF, emphasizing its advantages over conventional jet fuels and exploring various production pathways, including Hydrotreated Esters and Fatty Acids (HEFA), Fischer-Tropsch synthesis, and Alcohol-to-Jet processes [1]. It also addresses current advancements and challenges in SAF technology and adoption, providing insights into ongoing research and development [6].

The paper then analyzes the environmental impact of aviation, focusing on emissions from airports and the industry's broader ecological footprint. It discusses how SAF and other green aviation technologies can mitigate these impacts, supported by current research data [2]. Following this, the regulatory framework is examined, particularly SAF quotas and international policies promoting SAF adoption, especially in Europe, where mandatory quotas are set to commence [7].

In the latter sections, the social welfare and community impact of aviation emissions are explored, considering public perception and stakeholder engagement in promoting sustainable aviation practices. The paper concludes with a review of technological innovations beyond SAF, such as Power-to-Liquids (PtL) and hydrogen fuels, evaluating their potential to complement SAF in achieving a sustainable aviation future [8]. The final section summarizes key findings and discusses future research directions, highlighting innovative solutions like energy beaming from solar farms to further enhance aviation sustainability [5]. The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Sulfur Dioxide and Fossil Fuels

Sulfur dioxide (SO₂) emerges as a significant pollutant from the combustion of fossil fuels, with the aviation sector responsible for 11.2

2.2 Aviation's Contribution to Global Emissions

The aviation industry is a notable contributor to global greenhouse gas emissions, primarily through fossil fuel combustion in aircraft engines, accounting for about 2-3

In recent years, the aviation industry has increasingly focused on the adoption of Sustainable Aviation Fuel (SAF) as a viable strategy for reducing its environmental impact. As outlined in Figure ??, the hierarchical structure of SAF is depicted, offering a detailed overview of its characteristics and benefits. This figure categorizes the environmental and economic advantages of SAF, alongside various production pathways and the current advancements and challenges facing its implementation. By illustrating technological innovations and the obstacles to widespread adoption, the chart provides a comprehensive understanding of SAF's pivotal role in advancing sustainability within the aviation sector. Such insights are critical for informing both policy and practice in the pursuit of greener aviation solutions.

Figure 2: This figure illustrates the hierarchical structure of Sustainable Aviation Fuel (SAF), detailing its characteristics and benefits, production pathways, and current advancements and challenges. The chart categorizes environmental and economic benefits, diverse production methods, technological innovations, and the obstacles to widespread SAF adoption, providing a comprehensive overview of SAF's role in advancing aviation sustainability.

3 Sustainable Aviation Fuel (SAF)

3.1 Characteristics and Benefits of SAF

Sustainable Aviation Fuel (SAF) offers a promising alternative to conventional jet fuels, significantly reducing carbon emissions and advancing aviation sustainability. As illustrated in Figure 3, the key characteristics and benefits of SAF encompass its environmental advantages, economic feasibility, and innovative technological developments that support its adoption in aviation. SAF's environmental benefits include a marked decrease in carbon emissions, as evidenced by FT-SPK fuels derived from Municipal Solid Waste, which demonstrate substantial carbon reduction potential alongside favorable economic metrics [4]. Utilizing 100% HEFA-SPK fuel results in a 56% reduction in contrail ice particle numbers and a 35% decrease in soot emissions compared to standard Jet A-1 fuel [9].

The economic feasibility of SAF production is enhanced by a standardized benchmark for consistent comparisons across various methods, addressing cost disparities with fossil kerosene [10]. Incentive mechanisms are necessary to promote SAF adoption among airlines [6]. Innovative methodologies, such as Non-negative Matrix Factorization (NMF) for FTIR spectra analysis, enable accurate predictions of key fuel properties, optimizing production processes [11]. Numerical simulations of fixed bed catalytic reactors for CO₂-to-SAF conversion provide insights into chemical processes and operational optimization, advancing efficient production technologies [12].

Beyond SAF, hydrogen emerges as a promising alternative due to its high energy density and zero carbon emissions, aligning with sustainability objectives and reinforcing its role alongside SAF in reducing aviation's environmental impact [13, 14]. Innovative technologies highlight SAF's broader benefits, such as diminishing fossil fuel reliance and achieving cost savings in aviation, exemplified by methods like SoPhAr [5].

3.2 SAF Production Pathways

SAF can be produced through various pathways, each with unique advantages and challenges. The primary methods include hydroprocessed esters and fatty acids (HEFA), alcohol-to-jet (ATJ), and

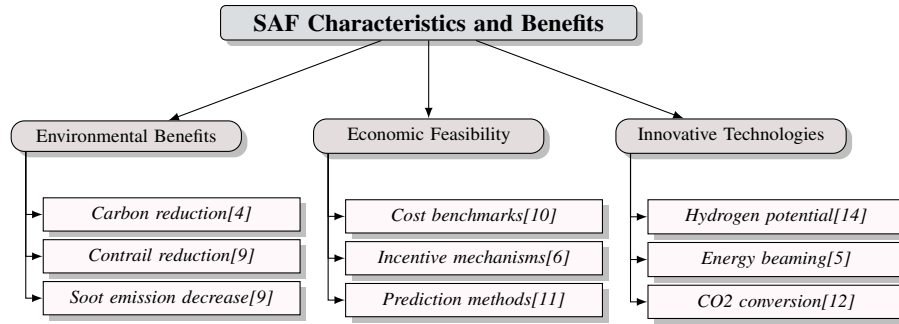


Figure 3: This figure illustrates the key characteristics and benefits of Sustainable Aviation Fuel (SAF), highlighting its environmental advantages, economic feasibility, and innovative technological developments that support its adoption in aviation.

Fischer–Tropsch synthesized paraffinic kerosene (FT-SPK), all approved under ASTM D7566 for aviation use [15]. These pathways utilize bio-based feedstocks, ensuring compatibility with existing infrastructure while reducing lifecycle carbon emissions.

The HEFA process involves hydrogenating vegetable oils or animal fats to produce high-quality jet fuel akin to conventional kerosene. Despite mature technology and refinery compatibility, it faces limitations due to the availability and sustainability of lipid-based feedstocks [1]. The ATJ pathway converts alcohols like ethanol or butanol into jet fuel through dehydration, oligomerization, and hydrogenation, offering feedstock flexibility from various biomass sources. However, high alcohol production and conversion costs hinder economic viability [15].

FT-SPK involves gasifying biomass to create synthesis gas, converted into liquid hydrocarbons via the Fischer–Tropsch process. This pathway accommodates diverse feedstocks, including municipal solid waste and agricultural residues, though gasification and synthesis complexity and capital intensity present economic and technical challenges [1].

Recent advancements explore converting CO₂ into SAF using innovative technologies. Numerical simulations integrating computational fluid dynamics (CFD) with heterogeneous catalytic reactions analyze CO₂-to-SAF conversion in fixed bed reactors, optimizing processes for enhanced efficiency and yield [12]. This approach represents a promising avenue for producing SAF from non-traditional feedstocks, potentially reducing the aviation sector’s carbon footprint further.

3.3 Current Advancements and Challenges

Advancements in SAF technology have improved production efficiency and reduced greenhouse gas emissions. Computational fluid dynamics (CFD) simulations elucidate CO₂ conversion to SAF, offering insights into hydrogenation processes and reactor performance under varying conditions [12]. These advancements optimize SAF production processes, aligning with the goal of minimizing aviation’s carbon footprint.

Despite technological progress, challenges impede SAF adoption. High production costs and infrastructure investments pose significant barriers [8]. Limited sustainable feedstock availability and ongoing research needs complicate economic viability [15]. Hydrogen-based systems, a promising alternative, face technological challenges, including cryogenic storage and aircraft design modifications [13].

Innovative methods for predicting SAF properties achieve high accuracy and interpretability, essential for advancing technologies [11]. However, SAF’s economic competitiveness against fossil kerosene requires incentive mechanisms for airline adoption [1]. Producing jet fuel from solar energy, while reducing lifecycle CO₂ emissions by 25%, incurs higher costs than conventional fuels, necessitating substantial investments [16].

Transitioning to SAF involves addressing safety concerns and infrastructure requirements associated with alternative propulsion methods, such as energy beaming, requiring careful consideration and investment [5]. While significant strides have been made in SAF technologies, achieving widespread

adoption requires coordinated efforts to overcome economic, technological, and infrastructural challenges [3].

4 Environmental Impact of Aviation

4.1 Airport Emissions and Environmental Impact

Airport emissions significantly contribute to the aviation sector's environmental impact, accounting for approximately 2% of global anthropogenic greenhouse gas emissions. With an anticipated four-to six-fold increase by 2050, Sustainable Aviation Fuels (SAFs) are crucial for mitigating these emissions. SAFs, which substantially lower carbon life-cycle emissions compared to traditional fossil fuels, are gaining traction amid impending European regulatory mandates. Hydrogen also emerges as a promising clean alternative, highlighting the need for innovative solutions to reduce aviation's environmental footprint [16, 14]. Airports emit pollutants such as CO₂, NO_x, particulate matter, and volatile organic compounds from aircraft operations, ground support equipment, and vehicular traffic, impacting local air quality and global climate change.

Figure 4 illustrates the key strategies for reducing airport emissions and their environmental impact, emphasizing the role of Sustainable Aviation Fuels, hydrogen as an alternative fuel, and innovative solutions such as energy beaming. SAFs are vital in reducing airport operations' carbon footprint. Replacing conventional jet fuels with SAF can significantly lower lifecycle greenhouse gas emissions, with some pathways reducing emissions by up to 80% compared to fossil fuels. This aligns with the Paris Agreement's climate targets. Regulatory measures like the European Commission's proposed blending mandate are expected to boost SAF use within existing aviation infrastructure [6, 16, 4, 15]. Moreover, SAF adoption can decrease other pollutants, such as SO₂ and particulate matter, enhancing local air quality around airports.

Regulatory frameworks and initiatives support SAF transition by promoting sustainable aviation practices, including mandates and incentives for increased SAF use in airline fuel mixes. However, challenges persist, particularly regarding SAF's economic viability against conventional fuels, necessitating incentive mechanisms. Innovative solutions like energy beaming, which transmits energy from solar farms to aircraft, are proposed to reduce fossil fuel reliance [5]. Evaluating these methods involves assessing energy transmission efficiency, safety, and economic feasibility.

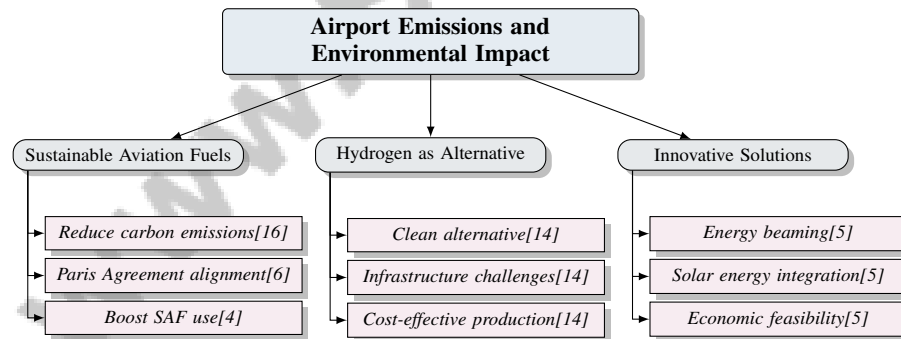


Figure 4: This figure illustrates the key strategies for reducing airport emissions and their environmental impact, with a focus on Sustainable Aviation Fuels, hydrogen as an alternative fuel, and innovative solutions such as energy beaming.

4.2 Green Aviation

Green aviation aims to minimize air travel's environmental impact through innovative technologies and practices. Central to this is transitioning from fossil-based fuels to SAFs, produced from renewable resources to significantly reduce lifecycle greenhouse gas emissions. Certain production pathways, such as Fischer-Tropsch and hydroprocessed esters of fatty acids, can cut emissions by up to 88

Beyond SAFs, green aviation explores alternative propulsion technologies, including hydrogen fuel and electric systems, offering significant emissions reduction potential. Hydrogen, capable of

achieving zero carbon emissions, is a viable long-term aviation decarbonization solution. Integrating these technologies requires advancements in aircraft design and infrastructure, alongside overcoming challenges related to storage and energy density [8].

Innovative approaches like energy beaming from solar farms to aircraft offer complementary solutions to reduce traditional fuel reliance. This involves transmitting solar energy to aircraft, aligning with sustainability goals [5]. Implementing such technologies requires careful evaluation of feasibility, safety, and economic viability compared to existing fuel options.

Green aviation also includes initiatives to enhance operational efficiency and reduce emissions through optimized flight paths, improved air traffic management, and lightweight materials in aircraft construction. These measures contribute to reduced fuel consumption and emissions, further promoting air travel sustainability [1].

5 Regulatory Framework and SAF Quotas

5.1 SAF Quotas and Regulatory Frameworks

SAF quotas are essential for advancing biojet fuel adoption and reducing aviation's environmental footprint. Current benchmarks often lack consistency in evaluating the economic viability of SAF pathways under similar policy conditions, emphasizing the need for harmonized standards to assess economic competitiveness across diverse production methods and regulatory contexts [10]. Policy frameworks play a critical role in incentivizing SAF production and adoption. The European Commission's blending mandate, which sets specific SAF usage quotas, aims to increase its share in aviation fuel, thereby driving market demand and encouraging investment in production technologies [1]. These frameworks are pivotal in fostering SAF development and commercialization, requiring coordinated efforts for substantial emissions reductions.

Comparative analyses of regulatory policies and incentives reveal their effectiveness in promoting SAF usage. Blending mandates, greenhouse gas intensity reduction targets, and financial incentives, such as tax credits and subsidies, are evaluated for their potential to lower emissions and enhance stakeholder collaboration [3, 6]. These incentives are crucial for narrowing the cost gap between SAF and conventional jet fuels, making SAF more attractive to airlines.

Promoting alternative fuels, including hydrogen, is also vital, with government policies and educational initiatives playing significant roles in their adoption within aviation [14]. Future research should focus on optimizing production processes, developing hydrogen distribution infrastructure, and establishing regulatory frameworks to facilitate alternative fuel adoption [8]. Such efforts are essential for transitioning to a more sustainable aviation industry, reducing reliance on fossil fuels, and mitigating climate impacts.

The ReFuelEU mandate, commencing in 2025, exemplifies the importance of SAF quotas and regulatory frameworks in aviation's sustainability transition. These measures aim to significantly reduce carbon emissions by mandating SAF use, which offers a lower life-cycle carbon footprint compared to traditional fuels. Effective SAF integration into existing infrastructure necessitates strategic collaboration among stakeholders, including airports, fuel suppliers, and aircraft operators, to comply with regulatory targets [15, 2, 6]. By establishing clear targets and providing financial incentives, these policies facilitate SAF and alternative fuel adoption, contributing to aviation's decarbonization and alignment with global climate objectives.

Figure 5 illustrates the categorization of SAF quotas and regulatory frameworks into three main areas: policy frameworks, alternative fuels, and economic viability. The figure highlights the key components and relationships within each category, emphasizing the role of blending mandates, financial incentives, and regulatory targets in policy frameworks. The alternative fuels section focuses on hydrogen adoption and the importance of optimizing production processes and infrastructure for their integration. The economic viability category addresses cost-related challenges and the market competitiveness of SAFs, underscoring the necessity for financial feasibility to promote SAF adoption. These examples collectively demonstrate the multifaceted approach necessary for advancing SAF adoption, balancing economic feasibility, regulatory mandates, and technological innovation [10, 7, 16].

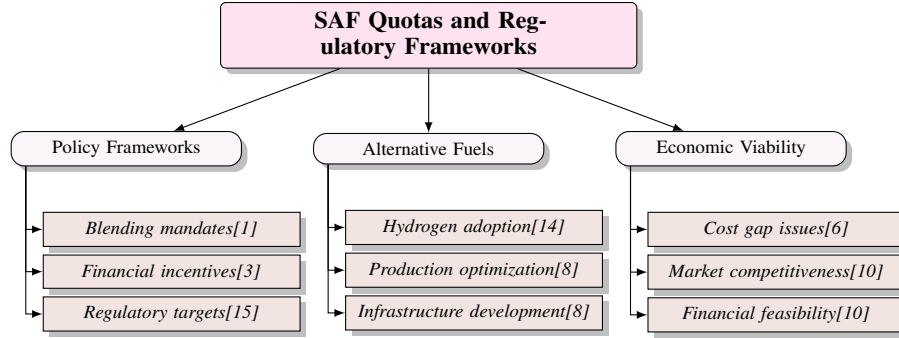


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5.2 International and Regional Policies

Benchmark	Size	Domain	Task Format	Metric
SAF-Benchmark[10]	6	Sustainable Aviation Fuel Production	Economic Viability Assessment	NPV, MSP
ECLIF3[9]	750	Aviation	Contrail Measurement	Apparent Ice Emission Index, Non-volatile Particle Emission Index
SAF-Bench[4]	5,000	Sustainable Aviation	Cost-Benefit Analysis	Net Present Value

Table 1: This table provides an overview of various benchmarks used to evaluate sustainable aviation fuel (SAF) initiatives. It includes details on benchmark size, domain, task format, and metrics used for assessment, highlighting the diversity and scope of current SAF-related evaluations.

International and regional policies are crucial in supporting SAF adoption and driving aviation’s sustainability transition. The European Union leads with initiatives like ReFuelEU Aviation, setting ambitious SAF blending targets [2]. This policy mandates a gradual increase in SAF’s share, fostering stable market demand and encouraging investments in production technologies.

Globally, the International Civil Aviation Organization (ICAO) has introduced the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), aiming to cap emissions at 2020 levels and promoting SAF as a key strategy [1]. CORSIA provides a framework for monitoring and reporting emissions and acquiring carbon offsets, incentivizing SAF integration into operations. Table 1 illustrates key benchmarks that are instrumental in assessing the effectiveness and economic viability of sustainable aviation fuel policies and initiatives.

Regional policies in North America and Asia enhance SAF adoption through financial incentives and support for research and development. In the United States, the Renewable Fuel Standard (RFS) and California Low Carbon Fuel Standard (LCFS) provide credits for SAF production and use, improving economic competitiveness against conventional fuels [3]. These policies create a conducive environment for SAF innovation and commercialization, facilitating the transition to a sustainable aviation sector.

Despite advancements, challenges remain in harmonizing international policies and ensuring consistent implementation across regions. Variations in regulatory frameworks, economic incentives, and technological capabilities can lead to disparities in SAF adoption rates, necessitating coordinated international collaboration [6]. Additionally, developing infrastructure for SAF distribution and establishing robust supply chains are essential for supporting the global scale-up of SAF usage.

6 Social Welfare and Community Impact

6.1 Community Well-being and Public Perception

Aviation emissions, including CO₂, NO_x, and particulate matter, pose significant risks to public health and environmental quality, necessitating a focus on Sustainable Aviation Fuel (SAF) initiatives. SAFs offer a promising solution with lower carbon life-cycle emissions compared to conventional fuels, aligning with global climate goals such as the Paris Agreement [14, 7]. Regions like Europe are implementing government mandates to decarbonize aviation, while alternative fuels like hydrogen are explored for their potential in achieving carbon neutrality. Communities near airports are particularly vulnerable to health issues, including respiratory and cardiovascular diseases, highlighting the need for sustainable aviation solutions.

Public perception is crucial for the success of SAF initiatives. Addressing concerns regarding the scalability, sustainability of feedstock, and integration within existing fuel supply chains is essential [3]. The long-term viability of SAF depends on renewable feedstock availability and efficient supply chains that meet sustainable fuel demands without compromising environmental integrity. Effective communication and stakeholder engagement are key to garnering public support. Educating communities about SAF's environmental benefits, such as reduced greenhouse gas emissions and improved air quality, can enhance public acceptance.

Figure 6 illustrates the key components of community well-being and public perception in relation to Sustainable Aviation Fuel (SAF) initiatives. It highlights the critical areas of aviation emissions, the benefits of SAF, and the importance of public engagement in promoting sustainable aviation practices. SAFs, with their lower life-cycle carbon footprint, play a vital role in the aviation industry's efforts to meet the Paris Agreement targets. By increasing awareness of SAF production pathways, such as HEFA and Fischer-Tropsch synthesis, communities can better understand the transition to sustainable fuels and the necessary policy frameworks and investments required for widespread adoption [6, 15]. Transparent discussions on SAF's scalability and sustainability can foster trust and encourage community involvement in promoting sustainable aviation practices.

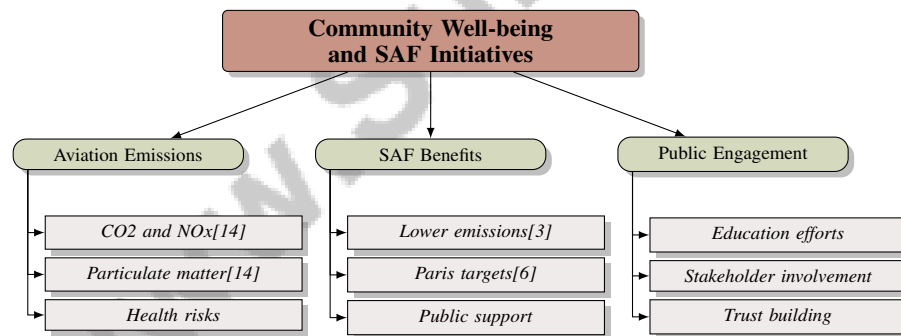


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6.2 Stakeholder Engagement and Collaboration

Advancing sustainable aviation practices, particularly through SAF implementation, requires robust stakeholder engagement and collaboration. Policymakers, industry leaders, aviation companies, and environmental organizations must work together to create a supportive environment for SAF adoption [4]. Policymakers are instrumental in developing regulatory frameworks and incentives that facilitate SAF production and utilization. They guide stakeholders, including airports and fuel suppliers, to align with initiatives like the ReFuelEU mandate, which aims to boost SAF adoption in the aviation sector. A comprehensive policy framework is needed to ensure sustainable biomass feedstock sourcing and support innovative technologies that advance SAF development [6, 2, 15]. Collaborative efforts between government agencies and industry stakeholders can foster innovation,

lower economic barriers, and facilitate SAF integration into existing aviation fuel supply chains, creating stable market demand and driving investment in production technologies and infrastructure.

Industry leaders, including airlines, fuel producers, and airports, play a pivotal role in transitioning to sustainable aviation by engaging in SAF implementation and adapting to regulatory frameworks such as the ReFuelEU initiative. Their involvement is critical for overcoming challenges related to fuel infrastructure, supply chain dynamics, and developing strategies that promote SAF uptake, facilitating the aviation sector's decarbonization efforts [16, 2, 15, 14, 7]. Collaboration among industry stakeholders aligns practices with sustainability goals and implements best practices for SAF production and utilization. Partnerships between airlines and SAF producers enhance supply chain efficiency and ensure a consistent supply of sustainable fuels. Additionally, industry collaboration fosters shared research and development efforts, accelerating technological advancements and reducing production costs.

Environmental organizations and community groups are crucial in stakeholder engagement, advocating for sustainable practices and holding industry players accountable. Their participation ensures that environmental and social considerations are integrated into SAF initiatives, fostering transparency and enhancing public trust by aligning industry practices with broader sustainability goals, as outlined in the ReFuelEU mandate [2, 15, 1]. Engaging with these groups facilitates public education campaigns that raise awareness about SAF benefits, improving public perception and acceptance.

7 Technological Innovations in Green Aviation

7.1 Alternative Fuels and Technologies

The exploration of alternative fuels and technologies is pivotal for sustainable aviation, aiming to mitigate the sector's environmental impact. Hydrogen and electric propulsion systems are prominent alternatives to conventional jet fuels, offering significant carbon emission reductions and enhancing sustainability in air travel. Hydrogen, with an energy-to-mass ratio of 120 MJ/kg compared to 43 MJ/kg for traditional jet fuel, enables performance comparable to conventional fuels while potentially reducing emissions by up to 74.7%. Its sole byproduct, water, contributes to environmental cleanliness. However, challenges such as cryogenic storage, optimal tank placement, and fueling infrastructure must be addressed for widespread adoption [13, 14].

Electric propulsion systems also offer sustainable benefits, though current limitations in energy density and range highlight the need for continued research and development to achieve carbon-neutral flight and minimize the aviation industry's environmental impact [8].

Beyond hydrogen and electric propulsion, innovative technologies like Power-to-Liquids (PtL) provide pathways to producing sustainable aviation fuels from non-fossil sources. PtL technology converts renewable electricity into liquid fuels, utilizing wind and solar energy to generate synthetic fuels with reduced carbon footprints [1]. Integrating PtL with existing fuel infrastructure allows a transition to sustainable fuels without significant modifications to current systems.

The development of alternative fuels and technologies, including SAFs derived from solar energy and hydrogen, is crucial for the aviation industry to significantly reduce its carbon footprint, which accounts for approximately 2% of global greenhouse gas emissions. With air travel projected to increase four to six-fold by 2050, adopting these cleaner energy sources is essential for achieving carbon-neutral flight and mitigating climate change impacts. Advancements in production methods, such as Fischer-Tropsch synthesis and Methanol-to-Fuels processes, alongside renewable energy systems, are necessary to enhance fuel efficiency and reduce emissions compared to traditional fossil fuels [16, 14]. Addressing technical and economic challenges associated with hydrogen, electric propulsion, and other innovative solutions will enable the aviation industry to significantly reduce its environmental impact and contribute to global climate goals.

7.2 Technological Innovations and Challenges

Integrating innovative green aviation technologies, including hydrogen and SAFs, is essential for addressing the environmental challenges posed by the aviation industry, which contributes approximately 2% of global anthropogenic greenhouse gas emissions. With an anticipated four to six-fold increase in air traffic by 2050, developing and implementing these technologies, supported by gov-

ernment policies and infrastructure enhancements, is crucial for achieving carbon-neutral flight and reducing aviation's carbon footprint [16, 14]. Innovations in SAF production, hydrogen fuel systems, and electric propulsion technologies offer substantial potential for reducing greenhouse gas emissions and minimizing the aviation sector's ecological footprint.

Significant progress has been made in SAF technologies, particularly in optimizing production pathways using renewable feedstocks. Processes such as Fischer-Tropsch synthesis and Alcohol-to-Jet (ATJ) are being refined to enhance efficiency and reduce costs [15]. However, the economic viability of SAF remains challenging due to high production costs and limited availability of sustainable feedstocks [1]. Policy support and incentive mechanisms are crucial to bridging the cost gap between SAF and conventional jet fuels, promoting broader adoption [6].

Hydrogen fuel systems represent a transformative approach to achieving zero carbon emissions in aviation, leveraging hydrogen's high energy density as an attractive alternative to traditional jet fuels. However, implementing hydrogen as a fuel source entails technological challenges, including cryogenic storage solutions and aircraft design modifications to accommodate hydrogen systems [13]. Establishing a robust hydrogen supply infrastructure is critical for supporting its widespread use in aviation [14].

Electric propulsion technologies offer another pathway for reducing aviation emissions. Electric aircraft, powered by advanced battery systems or fuel cells, can eliminate direct emissions from flight operations. Nonetheless, current battery technology limitations, particularly regarding energy density and weight, pose significant challenges for adopting electric propulsion in long-haul flights [8]. Continued research and development are essential to enhance battery performance and explore hybrid-electric systems that can extend the range and capabilities of electric aircraft.

Despite the challenges, technological innovations such as hydrogen fuel and SAFs present significant opportunities to mitigate the environmental impact of air travel. Hydrogen's abundance and zero carbon emissions during use position it as a viable alternative for carbon-neutral flight. Concurrently, advancements in solar energy-based SAF production methods, including Fischer-Tropsch and Methanol-to-Fuels processes, can reduce lifecycle CO₂ emissions by approximately 25% compared to traditional fossil fuels. Effective implementation of these technologies requires addressing issues related to government policy, education, and the overall value chain, ensuring a transition towards sustainable practices within the aviation sector [16, 14]. Collaborative efforts among industry stakeholders, policymakers, and researchers are essential to overcoming the technical and economic barriers associated with these innovations. By fostering innovation and supporting the development of sustainable aviation solutions, the industry can align with global climate goals and contribute to a more sustainable future for air travel.

8 Conclusion

8.1 Future Directions and Challenges

The progression and integration of Sustainable Aviation Fuel (SAF) and complementary green aviation technologies present a dual landscape of challenges and opportunities for future research endeavors. A critical area of focus involves reducing SAF production costs through technological advancements and enhanced efficiencies, which are pivotal for improving the economic feasibility of SAF and fulfilling broader climate goals. Additionally, research should delve into hybrid energy systems and alternative SAF production methods, particularly those that diverge from HEFA pathways, to alleviate competition with food resources and other biofuel markets.

A thorough investigation into the lifecycle emissions associated with alternative fuels, with a particular emphasis on hydrogen, is imperative. This includes assessing the impact of contrails formed from hydrogen combustion, which is crucial for understanding the long-term implications of employing

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Innovative technologies such as SoPhAr, which leverage energy beaming from solar farms, present promising avenues for reducing the aviation industry's reliance on fossil fuels. Future research should prioritize optimizing this technology for scalability, bolstering safety measures, and exploring further applications of energy beaming within the aviation sector.

Finally, fostering collaboration among stakeholders and crafting robust policies are essential for advancing SAF adoption. These efforts should aim to strengthen multi-stakeholder engagement and ensure that policies support sustainable aviation practices while addressing potential market competition. Tackling these research directions and challenges will empower the aviation industry to make substantial strides toward sustainability and mitigate its environmental footprint.

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