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A Critical Review of Decarbonization Strategies Among Major U.S. Airlines: Comparison Between Sustainable Aviation Fuel and Carbon Offsets

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Abstract

From the draft: airlines clearly look down upon having carbon offsets as a part of their net-zero plans, but from their lack of transparency and potential of other offset/reduction methods, offsets are still very essential to net-zero and their quality should thus be invested in more.

Keywords: decarbonization strategies, U.S. Airlines net-zero plan, sustainable aviation fuel, U.S. Airlines carbon offset

1. Introduction

In light of the commercial aviation industry's rapid expansion, climate advocates and stakeholders have become more vocal about the need for more sustainable flight methods. The airline industry currently accounts for 2.5% of terrestrial carbon emissions and 4% of global warming (Gössling, S., & Humpe, A., 2020). On its current path, global statistics show that the current 850 million annual tons of CO2 released by the airline industry are projected to triple by 2050. If other sectors decarbonize faster, aviation's share of global emissions could rise substantially by 2050. The U.S. aviation is a major player within this sector, contributing approximately 3% of global CO2 emissions. More than 94% of U.S. international aviation emissions come from en-route operations, primarily from the combustion of jet fuel (NASA, 2021).

In response, President Biden has set a target for the U.S. to achieve net-zero emissions by 2050, aligning with the goal established by the International Civil Aviation Organization (ICAO). This target, known as the Long-Term Aspirational Goal (LTAG) for international aviation, supports the UNFCCC Paris Agreement's temperature objectives by aiming for net-zero carbon emissions by 2050. The misalignment leads to a big question: How will the aviation sector align its rising emissions with the overarching goals?

To address the U.S. economy-wide goal of net-zero greenhouse gas emissions by 2050, the U.S. aviation sector is pursuing a basket of measures which trickles down to airlines' sustainability strategies. Being a significant contributor to global emissions, airlines and their collaborators have strived to incorporate alternative, sustainable practices and invested in numerous carbon mitigation methods. Two of these most prominent methods are purchasing carbon offset credits and investing in developing new technology, such as Sustainable Aviation Fuel (SAF) and Carbon Capture. Skepticism around these practices has become increasingly prominent. According to a Cambridge study (Thales A. P. West et al., 2023), 68% of the 89 million carbon credits expected to be generated by these 18 REDD+ sites in 2020, accounting for over 60 million credits, would have come from projects that barely reduced deforestation, and the remaining 32% have not conserved forest to the expected levels. For instance, rainforest carbon offsets verified by Verra, one of the most widely used certifiers of offsets, were "phantom credits" proven 90% ineffective and do not represent genuine carbon reductions. Meanwhile, its more promising alternative, SAF, exhibits dubious sustainability results as true impact on carbon emission varies by feedstock used to produce the alternative fuel — vegetable oil, corn ethanol, wastes and so forth — and the full lifecycle impact of new practices, particularly land use changes that could result in the loss of forests serving as carbon sinks.

In light of these trends, this paper investigates the following questions:

(1) Which one has stronger carbon mitigation potential, SAF or carbon offsets (CO)?

(2) Given the downsides of carbon offsets, can the aviation industry eliminate carbon offsets as an essential part of sustainability strategies?

(3) What are some risks associated with SAF and carbon offsets, respectively?

2. Research Methodology

The research design incorporates three main methods: literature review, comparative case study and meta analysis. These methods were chosen to provide a thorough understanding of current practices, efficacy, challenges, and opportunities in SAF adoption and voluntary carbon offsetting within the aviation sector.

(1) **Literature review.** A comprehensive review of academic research, industry reports, and aviation companies' annual/ sustainability reports is conducted, aiming at:

- Summarize existing research on SAF and voluntary carbon offsetting.
- Identify key trends, challenges, and opportunities in the adoption of these practices.
- Establish a theoretical framework for analyzing sustainable practices in the aviation industry.

(2) **Comparative case study.** This method aims to examine the sustainable practices of major United States airlines regarding SAF and carbon offsetting and seek to assess the impact of these practices on reducing the carbon footprint of airlines. The comparative case study will employ a cross-case synthesis to identify common themes, differences, and unique practices among the selected airlines. The analysis will focus on:

A. The types and sources of SAF used.

B. The scope and implementation of voluntary carbon offsetting programs.

C. The reported outcomes and effectiveness of these practices.

D. Challenges faced and strategies employed to overcome them.

8 US airlines are selected based on their number daily flight to compare their sustainability strategies, especially their approach to SAF and CO:

Airlines	Indicators
• American • United • Delta • Southwest • Alaska • JetBlue • Frontier • Hawaiian	1) Sustainability strategies • Sustainability goals • Carbon reduction timeline and roadmap 2) Comparison between SAF/ CO strategies • Availability of SAF/CO mechanism • Expected impact/efficacy (tons annually) of SAF/ CO • Investment (USD) in SAF/ CO • External provider of carbon offsets • Preference for SAF/ CO • Planned strategies on adopting SAF/ CO

(3) **Meta analysis.** Data will be collected from multiple sources, including airline sustainability reports and official websites, industry databases and publications, and reports/ policies from government, regulatory bodies or international organizations.

3. Global Context for Sustainable Aviation

3.1 Environmental Impact of Aviation

Aviation activities impact the global environment by contributing to climate change, affecting air quality, and increasing aircraft noise. Fossil fuel combustion by aircraft engines produces approximately 71% CO_2, 28% water vapor, and less than 1% of CO, HC, NO_x, SO_x, and primary $PM_{2.5}$, also known as atmospheric particulates. The aviation sector contributes around 2.5% of the world's carbon emissions. Following the COVID-19 pandemic, rising global transportation demand has led to even higher emissions. Non-CO_2 emissions from aviation, such as NO_x, SO_x, and primary $PM_{2.5}$, contribute to air pollution and, along with aircraft noise, impact human health.[1234]

3.2 US Sustainable Aviation Policies and Frameworks

- ICAO assumes leadership in reducing CO2 in the aviation industry. Core strategies to achieve its 2050 net-zero emissions goals include advancing sustainable aviation fuels (SAF), improving fuel efficiency, and exploring electrification technologies.
- **The U.S. Government Aviation Climate Action Plan:** https://www.icao.int/SAM/Documents/2024-ENVSEM/4_FAA%20AEE%20-%20Climate%20Action%20Plan.pdf

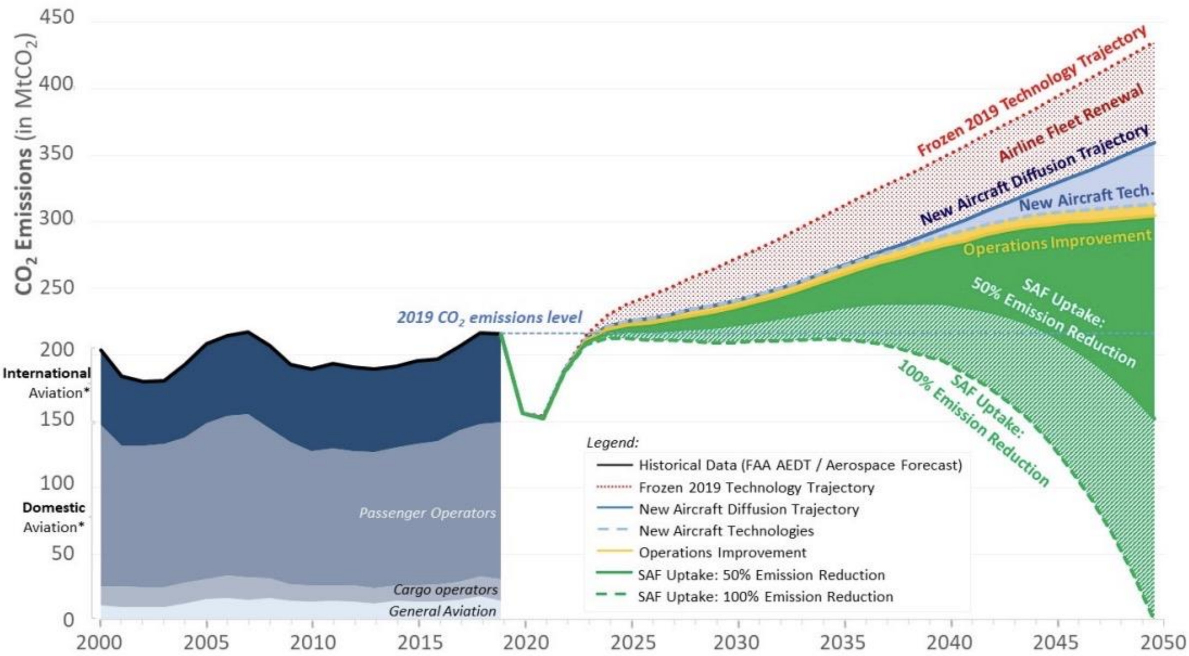

Figure 1. Aviation climate goals and decarbonization goals of the United States (2000~2050)

Source: 2021 United States Aviation Climate Action Plan.

3.3 Corporate Responses: Sustainable Aviation Fuel and Carbon Offsets

3.3.1 Sustainable Aviation Fuel as an Emerging Carbon Reduction Technology

Sustainable aviation fuel is an alternative fuel made from non-petroleum feedstocks, including but not limited to, the food and yard waste portion of municipal solid waste, woody biomass, fats/greases/oils, and other feedstocks. It features fewer greenhouse gas (GHG) emissions and more flexibility. 100% SAF is expected to have the potential to reduce by up to 94% of GHG emissions compared to traditional jet fuel, depending on feedstock and technology pathway. (US Department of Energy, 2024)

While SAF production is in its early stages, the volume starts to pick up with rising market penetration. According to the ICAO, over 360,000 commercial flights have used SAF at 46 different airports largely concentrated in the United States and Europe[5] — set to surge 98% to 1.95 million mt in 2024 (S & P Global, 2024).

Sustainable Aviation Fuel (SAF) presents several key challenges that hinder its scale-up adoption and effectiveness.

(1) **The primary obstacles is cost.** SAF is significantly more expensive than conventional jet fuel, often costing several times more. This cost premium is a major deterrent for airlines, as profit margins in the industry are typically thin. Despite the potential environmental benefits, airlines face economic barriers in scaling up SAF use without further financial incentives or policy interventions (Naya Olmer & Dan Rutherford, 2017; Jennifer L, 2024).

(2) **Limited production capacity.** In 2022, SAF accounted for less than 0.1% of total jet fuel used by U.S. airlines, far from the ambitious goals set by governments and international bodies (GAO Highlights, 2023). The infrastructure and technology required to ramp up SAF production are capital-intensive and

time-consuming, leading to slow progress in increasing supply. This is associated with Feedstock availability, which also poses a challenge. SAF can be produced from a variety of renewable sources, including agricultural residues, waste oils, and non-food crops. However, the sustainable supply of these feedstocks, especially in large quantities, is uncertain. Competing uses for these resources, like food production or other biofuel markets, may constrain availability and drive up costs (Damien Beillouin, Marc Corbeels, Julien Demenois, David Berre, Annie Boyer, Abigail Fallot, Frédéric Feder & Rémi Cardinael, 2023).

(3) Technical limitations. Current regulations restrict SAF blending with conventional jet fuel to a maximum of 50%. This limitation impacts the ability of airlines to fully transition to SAF. Moreover, alternative technologies such as electric and hydrogen-powered aircraft, while promising, are not yet viable for large-scale, long-distance commercial flights (Abhishek Sinha, 2024).

3.3.2 Carbon Offsets

Carbon credits, also known as carbon allowances, are permits granted by external entities that allow their holders to emit a designated amount of carbon dioxide or equivalent greenhouse gases (GHG), typically quantified as one metric ton of CO2. These credits are pivotal within carbon offset schemes, which enable individuals or organizations to balance their emissions by funding projects that either sequester or mitigate GHGs. In these voluntary carbon markets, for every credit purchased, an equivalent amount of carbon dioxide is offset, aligning businesses and industries, such as aviation, with their carbon-neutral objectives.

For corporations, the carbon offset process allows them to offset their own emissions by investing in external projects — often renewable energy, reforestation, or methane capture — meant to reduce emissions elsewhere. This method provides a transparent, measurable approach to achieving climate targets while remaining operationally feasible, especially in sectors where fully eliminating emissions may be technologically or economically challenging. By supporting external projects, companies can fulfill or make progress toward their sustainability goals while demonstrating environmental responsibility.

These credits provide a pathway for industries that are hard to decarbonize, like aviation, to compensate for residual emissions, allowing them to participate in the global effort to combat climate change while simultaneously enabling the funding of essential conservation and climate-positive initiatives.

However, there is often skepticism around the quality of some carbon credits, particularly regarding their additionality, permanence, and non-leakage — the key attributes that determine their legitimacy. While carbon credits are vital for financing environmental projects that might not receive funds otherwise, concerns about greenwashing still exist when businesses claim neutrality without fully addressing their core emissions. Thus, while effective, the system requires diligent regulation and transparency to avoid misuse or overreliance on offsets as an alternative to reducing emissions at the source.

According to various research done by American Forest Foundation(www.forestfoundation.org), the Integrity Council (icvcm.org), the Greenhouse Gas Management Institute and the Stockholm Environment Institute (ghginstitute.org) and other research organizations, a credible carbon credit must possess three key attributes:

(1) Additionality: The emissions reduction must occur as a direct result of the project that would not have happened without the carbon credit's financial support.

(2) Permanence: The carbon offset must last for a long period, often considered to be at least 100 years, ensuring that the offset remains intact and continues to sequester or prevent emissions.

(3) Non-leakage: The project must not cause an increase in emissions elsewhere. For example, protecting one forest should not lead to deforestation in another area.

However, there is often skepticism around the quality of some carbon credits. One form of greenwashing is green crowding, where companies attempt to obscure accountability by collectively relying on the same third-party verifiers (e.g., Verra) without thoroughly assessing the legitimacy of the offsets. This can sometimes undermine the actual impact of carbon offset initiatives.

Despite criticisms, carbon credits play an essential role in funding critical environmental conservation efforts. For instance, money from carbon credits often supports the protection of ecosystems that might otherwise suffer from deforestation or degradation. Nonetheless, concerns have been raised, particularly in the forestry sector, where some carbon credits may be based on overly optimistic or flawed baselines, yet are still marketed as part of "carbon-neutral" or net-zero pledges by industries like aviation. In short, while carbon credits can be a useful tool in the fight against climate change, they must be carefully vetted for quality to ensure they deliver the promised environmental benefits without contributing to misleading practices like greenwashing.

3.3.3 Comparison between SAF and CO

From the draft: While carbon offsets are the temporary solution for airline sustainability, sustainable aviation fuel (SAF) is the most prominent long-term solution in the airline industry. However, while SAF is crucial to aviation's decarbonization strategy, overcoming these economic, infrastructural, and technological barriers is essential for its broader adoption and success. The table below summarizes the effectiveness, cost, availability, and externality of each one of the approaches.

	Sustainable Aviation Fuel	Carbon credit offset
Effectiveness	• SAF can effectively reduce GHG by 50% to 94% compared to conventional jet fuel. • The actual GHG reduction impact largely depends on the choice of feedstock and technology pathway.	• Allow the sector to decarbonize the residual emission through purchasing carbon credits that are generated by projects that can eliminate emissions. However, the effectiveness of some carbon credits are uncertain and challenging to verify. • No direct impact on in-sector GHG emission reduction.
Cost	• 2 to 5 times higher cost compared to jet fuel depending on the feedstock and conversion pathway, around USD 2,400/ton.	• 0.4% to 2.4% of projected jet fuel prices from 2021 to 2035, assuming $15 to $20/ton offset in 2035.
Availability	• Constrained by the domestic feedstock that are available for SAF production. • Uncertainty of reliable data, such as the yields for commercial-scale energy cropping, the evaluation of future availability of biomass.	• The number of credits issued each year is typically based on emissions targets. • The demand for carbon credits (e.g. CORSIA carbon credits) is expected to be much higher than the supply. The International Air Transport Association (IATA) has warned of a shortage of credits, which will become negative by 2030.
Externality	• Consumption of conventional SAF feedstocks could pose indirect impacts such as food price spikes, land conversion, and indirect GHG emissions when feedstocks are diverted from existing end-uses.	• The potential disqualified carbon credits that are available in the carbon market could undermine the goal of GHG reduction across multiple sectors.

4. Comparative Analysis

Table 1. Comparison of 8 major US airline's SAF/ CO strategies version 2

Airline	**Overarching goals and investment in decarbonization strategy**	**CO**			
		Time of CO adoption	**CO provider company**	**VCO mechanism**	**Plan on phasing out CO**
American	10,000 tons of permanent carbon removal by 2025; Partnered with Breakthrough Energy Catalyst; Invested $100 million towards clean energy technologies	Not adopted but acknowledges likely future need	Graphyte; Carbon casting removes & stores CO2 (direct air capture), 10,000 tons of permanent carbon removal by 2025. Partners with cool effect to make VCO possible; Cool	Yes	No

			Effect Graphyte		
United	Net zero GHC by 2050, no CO. With interim goal of 50% carbon emission intensity by 2035 compared to 2019[6]	Not part of roadmap	Not part of roadmap	Yes	No
Delta	Net zero GHC by 2050, fuel-efficient aircraft, increasing use of SAF enhancing operations	No	No	No	Explicitly says that they have fully transitioned away from focusing on carbon offsets
Southwest	Reduce carbon emission per revenue ton kilometer by 25% by 2030 and 50% by 2035[7] Launch of Southwest Airlines Renewable Ventures (SARV) and $30 mil investment to LanzaJet (Southwest Airlines, 2024)	Carbon capture is 13% of their operations, mention direct air capture in future	Offsets are used in case their other plans do not work Support The Guatemalan Conservation Coast; Delta Blue Carbon, Kootznoowoo Improved Forest Management project	Yes	no
Alaska	net-zero by 2040 Carbon Direct partnership	No public data available but	Doyon Native Community Forest Project: Freres Biochar; The Guatemalan Conservation Coast	Yes	no
JetBlue	net-zero by 2040, not 2050! JetBlue ventures — support and invest in lower-emissions aircraft	used CO to completely offset all domestic from 2020-2022	carbonfund.org, EcoAct, South Pole (2020-2022), now Rubicon Carbon, joined BSR BASCS, expect to continue with carbon offsets	Yes[8]	no
Frontier	Fuel-efficient fleet; Flight route; optimization; reduce aircraft weight; Pay Charm to remove CO2; Purchase SAF; Support Pratt & Whitney engine dev.	No public data available	Vaulted Deep, Charm Industrial	No	Pay Charm Industrial $53 million to remove 121,000 tons of CO2 between 2024 and 2030 (Catherine Clifford, 2023)
Hawaiian	preventing the emission of 18	Start from April 2022[10]	Conservation International; VCO, don't mention non	Yes	No

	million tons of carbon dioxide equivalent over the next 30 years; protected in 2023 3,780 acres of forest[9] Purchase SAF from Gevo; Partner with PAR Hawaii and Pono Pacific to develop new fuels		VCO offsets[11]		

Continued Table

SAF			
SAF partner	**Decarbonization goals from SAF**	**SAF adoption remark**	**more notes**
Infinium for SAF from Project Roadrunner	10% by 2030 Reduce ~40 million of metric tons of CO_2[12]		SBTi verified reduce ghg goals but it doesn't say that net zero by 2050 is verified, also contrail avoidance.
Dimensional Energy Neste Svante	58% by 2050[13]	0.1% of total fuel usage as of Dec 2023	SBTi-validated mid-term targets; currently, SAF only 0.1% (openly acknowledges). SAF used by united has 85% reduction potential (while others have 80%)
Minnesota SAF Hub Neste	47% by 2050[14]	10% SAF by end of 2030 35% SAF usage by 2035 95+% by 2050[15]	SBTi-validated target: reduce GHG by 45% in 2035. 3.5M gallons of SAF delivered in 2023. ACKNOWLEDGES THAT SAF IS NOT EMISSIONS-FREE, MEDIUM TERM
SARV, USA Bioenergy Velocys LanzaJet Neste Marathon Petroleum and Phillips 66[16]	10% by 2030; 25% emissions reduction by 2030, 50% by 2035, save 1.1 billion gallons of jet fuel by 2035	Jan 2022	
began eco-skies alliance to invest/garner support for SAF CHOOOSE	decrease carbon emissions by 50% by 2035	Partner with Microsoft to reduce business travel emissions[17]	first commercial U.S. airline to fly multiple routes using the alternative fuel in 2011
Neste World Energy World Fuel [18]	10% by 2030	flying on SAF out of San Francisco (SFO) since 2020 and LAX since 2021, JFK 2024	SBTi-validated target: reduce GHG related to jet fuel 50% by 2035
Nest, SkyNRG	Not specified	In May 2023, agreement for the	

CleanJoule		right to purchase up to 90 million gallons of SAF (Frontier Airlines, n.d.)	
2023: will buy 10 million gallons of SAF annually from Gevo for 5 years, begin in 2029	decrease life-cycle jet fuel emissions per revenue ton mile by 45% by 2035[19]	replace 10% of conventional jet fuel with SAF by 2030[20]	SAF costs 2-5x that of conventional jet fuel; currently, SAF can only be blended 50/50 but is "expected to increase substantially"

Source: public information and data compiled by author.

Table 1 compares the sustainability practices of eight major airlines, focusing specifically on Sustainable Aviation Fuel (SAF) and Carbon Offsets (CO). The analysis reveals that SAF consistently appears as a primary solution in airline sustainability strategies aimed at reducing emissions. For instance, airlines like JetBlue prominently feature SAF in their sustainability reports, often discussing it alongside other initiatives like fuel optimization. This emphasis reflects the aviation sector's reliance on SAF in their pursuit of net-zero carbon emissions, despite significant challenges such as limited production capacity and the unclear future of widespread SAF adoption, as mentioned in previous sections. It is precisely such limitations of SAF that raise important questions about the feasibility of airlines' sustainability goals. The current production levels of SAF are insufficient to meet the global demand for fuel in aviation, and the infrastructure to scale SAF production is still in its nascent stages. As a result, the financial and environmental sustainability of SAF is uncertain, making it questionable whether airlines can realistically meet their ambitious net-zero targets relying primarily on this technology.

Moreover, the transparency surrounding the actual usage of SAF is problematic. Among the eight airlines analyzed, only United Airlines disclosed the percentage of SAF blended with traditional jet fuel during operations. In contrast, other airlines, such as Spirit Airlines, either explicitly declined to provide this information or omitted it entirely from their reports. This lack of transparency raises concerns about potential greenwashing, where companies may overstate their sustainability achievements without providing clear, verifiable data. The reluctance to disclose SAF usage points to a gap between the sustainability goals presented by airlines and their actual implementation. This discrepancy undermines the credibility of their environmental commitments, and in the long term, could erode trust in the aviation sector's ability to achieve true carbon neutrality.

Beyond SAF, many airlines offer Voluntary Carbon Offsets (VCOs) as a method for customers to neutralize their emissions from flights. VCO programs allow individuals to offset emissions by contributing to projects like reforestation or renewable energy development. However, there is growing skepticism around the effectiveness and legitimacy of these offsets. According to the International Air Transport Association (IATA), only 1-3% of airline customers opt to purchase offsets, reflecting widespread distrust in the efficacy of such programs. Critics argue that carbon credits, especially those tied to nature-based projects, may not provide the permanent or additional reductions in emissions that airlines claim. This has led to concerns about the validity of "carbon-neutral" claims in aviation.

Despite these concerns, some airlines, like Hawaiian Airlines, continue to support nature-based offsets through partnerships with organizations like Conservation International. These programs fund conservation efforts in areas such as Chuyulu Hills in Kenya, which contribute to preventing millions of tons of CO_2 emissions over time. Hawaiian Airlines is relatively transparent about its offset providers, unlike others like WestJet and JetBlue, which vaguely reference "high-integrity" or "ICAO-approved" sources for their offset purchases.

It is important to note that SAF itself, while offering up to an 80% reduction in emissions compared to conventional jet fuel, cannot completely eliminate aviation's carbon footprint. Even with widespread SAF adoption, airlines would still face residual emissions, requiring other strategies — such as operational efficiency and emissions reductions — to bridge the gap. However, without the inclusion of carbon offsets, achieving net-zero emissions is almost impossible for the sector due to the remaining operational emissions that cannot be eliminated.

Moreover, some airlines have started to invest in Direct Air Capture (DAC) technology, which removes CO_2 directly from the atmosphere for storage or reuse. This innovative approach, though in its nascent stages, represents a potential complement to SAF and carbon offset programs, offering a direct method for airlines to address their carbon emissions in the longer term.

In conclusion, while SAF and carbon offsets play critical roles in airlines' sustainability strategies, there are significant challenges in transparency, efficacy, and the reliance on placeholder solutions like offsets. Airlines need to adopt a more comprehensive and credible approach, balancing immediate emissions reductions with innovative technologies like DAC, to truly achieve their net-zero ambitions.

5. Limitations of This Research

(1) **Reliance on Airline Sustainability Reports.** A key limitation of this research is the heavy dependence on airline sustainability reports and articles critical of carbon offsets. Many airline reports exhibit significant transparency issues, often failing to disclose their current progress towards net-zero goals in a clear and quantifiable manner. Instead, these reports typically focus on future projections without providing concrete, verifiable data on present-day emissions reductions. The absence of detailed, empirical evidence makes it difficult to assess the effectiveness of sustainability strategies such as Sustainable Aviation Fuel (SAF) or carbon offsets. This lack of transparency introduces ambiguity into the research, leaving gaps in understanding which strategies genuinely mitigate emissions and which may contribute to greenwashing.

(2) **Questionable Validity of Carbon Offsets.** Much of the available data on sustainability in the aviation sector comes from sources that are critical of carbon offsetting practices. These sources frequently question the reliability of carbon offset suppliers, casting doubt on whether carbon credits truly mitigate emissions as airlines claim. This skepticism further complicates the evaluation of carbon offset schemes, as many offsets are marketed as solutions while their actual impact on emissions reduction remains questionable. The absence of reliable, consistent, and publicly available data on offsets hinders the ability to objectively measure the feasibility of airlines' long-term sustainability goals.

(3) **Bias in existing literature.** Current literature tends to focus heavily on the flaws of carbon credit suppliers rather than on assessing the overall effectiveness of sustainability strategies across the aviation industry. While many critiques target the shortcomings of carbon offsets, less attention is given to evaluating broader decarbonization strategies, such as SAF integration or operational efficiencies, within the sector. This creates an incomplete picture, as it overemphasizes the problems of carbon offsets while underrepresenting other critical aspects of airlines' sustainability efforts.

(4) **Lack of publicly available data and comparable metrics to gauge the decarbonization effect/ potential of SAF/ CO.** Regarding both SAF and carbon offsets, there is a notable lack of publicly available, comparable data. The inability to consistently quantify the decarbonization effects of these methods makes it difficult to objectively evaluate their impact. Corporate reports are often vague or make arbitrary assertions, leaving researchers with limited resources to assess the feasibility and effectiveness of airlines' sustainability claims. This lack of transparency, coupled with the growing concern over potential greenwashing, poses challenges for determining whether the aviation industry can realistically achieve its net-zero goals. Consequently, these limitations diminish the accuracy and reliability of the research findings.

6. Conclusion

6.1 Key Findings

1) SAF, as one of the main technologies to decarbonize the aviation sector is expected to have the potential to reduce by up to 94% of GHG emissions compared to traditional jet fuel. Even though, its effectiveness in carbon reduction depends heavily on feedstock and technology pathway.
2) The ramp up of SAF adoption is slow regardless of its great decarbonization potential. Currently, SAF is several times more expensive than conventional jet fuel. The production capacity of SAF is limited by the feedstock availability and the capital-intensive and time-consuming infrastructure and technologies. Thus, policy interventions are needed to guide and support the scale up of a truly carbon-reducing SAF production and adoption.
3) Carbon offset enables airline corporations to achieve their decarbonization targets by funding projects that either sequester or mitigate GHGs. It provides a transparent and measurable approach to eliminate residual emissions that are technologically or economically challenging to achieve.
4) Nevertheless, there is increasing concerns around the quality of carbon credits. The skepticism focuses on whether the invested projects that generate carbon credits can fulfill its intended purpose of reducing carbon emissions. Therefore, the system requires diligent regulation and transparency to avoid misuse or overreliance on offsets as an alternative to reducing emissions in the aviation sector.
5) Although carbon credit offset is needed to get the aviation sector to net-zero, every technological effort to reduce in-sector emissions should be explored and implemented first, considering the serious questions raised about offset integrity.

6.2 Recommendations

1) Governments need to adoption policies to accelerate the scale up of SAFs, such as proposed mandates by European Union and United Kingdom and incentives such as the Low-Carbon Fuel Standard adopted by California in the United States. Early adoption of SAFs could help to reduce cost faster in the long term.

2) Governments need to clearly define the sources to produce SAFs and ensure the allowed SAFs would reduce significant emission (e.g. over 50%) over their life cycle after taking into account of land use change and displacement emissions. Food-based biofuels should be excluded from SAFs due to their sustainability risks.

3) Establish standards and mechanism to validate the effectiveness of carbon credit available in the carbon market for offsets, to make sure the credit purchased through the carbon market would have real-world effect in neutralizing the carbon emissions from the aviation sector.

4) Establish simplified monitoring, reporting, and verification procedure for governing the types of offsets allowed in the carbon market. The annual emissions data should be made available to the regulatory agencies and the public for transparency.

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