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The role of sustainable aviation fuel in CORSIA: An economic analysis

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ABSTRACT

Under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), airlines can decarbonize their operations by purchasing either sustainable aviation fuel (SAF) or carbon offset credits. We develop an economic model to compare airlines' profits and social welfare outcomes under different scenarios. We first assume that SAF and offset credits are equal, and then we introduce a SAF multiplier that promotes SAF usage. Our findings show that for SAF to be more profitable for airlines, its unit cost must be lower than that of offset credits. Additionally, if uncompensated emissions of SAF and offset credits are high, SAF needs greater economies of scale to be more socially beneficial than profitable. We also find that when airline competition increases, lower economies of scale for SAF production are needed for SAF to be cheaper or more beneficial than offset credits. Finally, a small SAF multiplier can reduce the appeal of SAF for airlines and society, while a SAF tax credit enhances its benefit.

1. Introduction

In recent years, greenhouse gas (GHG) emissions from civil aviation have gained much attention as the sector accounts for 2–3 % of total human emissions and is notoriously difficult to decarbonize. More importantly, despite Covid-19's impact on aviation, the industry continues to grow. To address this challenge, the 39th session of the International Civil Aviation Organization (ICAO) adopted the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) in 2016. CORSIA will be implemented in phases: a voluntary pilot phase from 2021 to 2023, a first phase from 2024 to 2026, and a second phase from 2027 to 2035. Mandatory participation will be required during the second phase (except for exempted states[1]). As of January 1, 2024, 126 countries have announced their intention to participate in CORSIA (ICAO, 2023). However, some countries like Brazil, China, India, and Russia have not confirmed their participation or seem likely to skip the pilot phases.[2]

The non-participation of these states has significant implications for the coverage and ambition of CORSIA. According to a study by the International Council on Clean Transportation (ICCT), the 12 non-participating states accounted for about 22 % of the global international aviation emissions in 2018, and their emissions are projected to grow by 150 % by 2035. As a result, CORSIA will only cover about 63 % of international aviation emissions from 2021 to 2035, instead of the expected 80 %. This also means that CORSIA will only achieve a 2.5 % reduction in CO2 emissions compared to the baseline scenario, instead of the 6.2 % reduction that was initially estimated.

CORSIA tracks and credits emissions reductions from international aviation toward carbon-neutral growth after 2020. ICAO is developing a carbon accounting framework and eligibility requirements for using

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[1] According to the ICAO Assembly Resolution A39–3, the second phase of CORSIA has two types of exemptions based on aviation-related criteria or socio-economic indicators. The first type applies to states with less than 0.5 % of the total international aviation activities in Revenue Tonne Kilometers (RTKs) in 2018, or those not in the top 90 % of individual RTKs. The second type includes least developed countries, small island developing states, and landlocked developing countries, which have special circumstances and can choose whether to join CORSIA or not.

[2] These states have various reasons for opting out of CORSIA, including concerns over the environmental effectiveness, economic impacts, and fairness of the scheme. Some argue that CORSIA does not reflect the principle of common but differentiated responsibilities and respective capabilities (CBDR-RC), meaning developed countries should lead in addressing climate change and support developing nations. Others also question the quality and availability of the carbon offsets that CORSIA will use, and the potential implications for their domestic aviation sectors and national interests.

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Sustainable Aviation Fuel (SAF) within CORSIA to claim emissions reductions.[3] SAF is a clean alternative to fossil jet fuels derived from feedstocks fulfilling a set of sustainability criteria.[4] Using SAF instead of conventional jet fuel can reduce carbon emissions by up to 95 %, depending on the feedstock and technology used (Prussi et al., 2021).[5] SAF is considered a key short-term option for reducing the aviation industry's carbon footprint. Unfortunately, while SAF can generate emissions reductions toward the CORSIA target, the primary mode of compliance is expected to be purchasing out-of-sector carbon offsets. The International Air Transport Association (IATA) asserts that CORSIA does not promote SAF, as the cost of purchasing SAF is much higher than purchasing carbon offsets, putting them at an economic disadvantage within the program (Liao et al., 2024). Though CORSIA provides a methodology for crediting emissions reductions from SAF, ICAO states that deploying SAF is the responsibility of individual nations (Pavlenko, 2021).

This design presents several challenges. Firstly, carbon credits have inherent limitations: some may not be genuine or beneficial, there are risks of double counting, and they only offset emissions temporarily. Therefore, carbon credits should be used cautiously and supplemented with cleaner technologies, sustainable fuels, operational improvements, and regulatory policies. Conversely, SAF is a form of "carbon insetting", where airlines invest in carbon reduction projects within their value chain. This approach offers more efficient and long-term benefit compared to offsetting. Furthermore, many studies suggest potential economies of scale for SAF production[6] (e.g., Wolff and Riefer, 2020; Overton, 2022; Takebayashi and Yamaguchi, 2024; Zheng et al., 2024). Since SAF is currently 4 times more expensive than carbon credit in the EU Emission Trading Scheme (EU ETS) market, carbon offsetting is sometimes suggested as a temporary solution until more SAF can be produced and sold at a similar price to fossil fuel (Magdalina, 2021). However, if offsetting remains the primary strategy for aviation decarbonization, what will drive the demand for SAF necessary to scale up its production?

Against such background, the goals of the regulator and the airlines may not be aligned. In particular, if economies of scale for SAF production are strong enough, it may be socially optimal for all airlines to use SAF, helping achieve the critical volume needed to reduce its unit cost. However, individual airlines may find it more profitable to deviate from this collaboration and opt for carbon offsets instead. Airline competition also plays a role here. Increased competition results in more passengers, boosting SAF usage and lowering production costs. However, more competition will also increase the negative externality an airline can have on other airlines by choosing to buy carbon offset credits.

Some potential remedies have been proposed, with a SAF multiplier being one of the most discussed (e.g., Pavlenko, 2021; Gozillon, 2022). A multiplier increases the value or benefit of a product or technology compared to its alternative. For example, if electric vehicles have a multiplier of 5, each electric vehicle is counted as 5 conventional combustion engine cars in regulations or policies like tax credits or subsidy. Multipliers have been utilized in various renewable energy sectors. For example, electricity from zero-carbon sources has also been encouraged by multiplier policies in different regions. Article 27 of the EU Renewable Energy Directive II has a 1.2 multiplier for SAF. In aviation, advanced biofuels and Renewable Fuels of Non-Biological Origin count as 1.2 times their energy content, while in maritime transport, they count as 1.5 times (Wissner and Graichen, 2024). Similarly, a SAF multiplier can be given to airlines buying SAF instead of carbon offset credits to fulfil their decarbonization goal. However, although this measure decreases the cost of purchasing SAF, it also has clear drawbacks. Firstly, a SAF multiplier will reduce the required GHG offsets from the aviation sector, leading to negative environmental consequences. Secondly, the multiplier also reduces the total amount of SAF needed for any given airline traffic, making it even harder to scale up SAF production and reduce its unit cost.

Therefore, it would be useful to investigate the following research questions. First, under what conditions would airlines choose SAF over carbon offsets when the two are treated equally for decarbonization? Second, how would the conditions change to make SAF a socially better option than carbon offsets? Third, what are the impacts of airline competition? Fourth, can a SAF multiplier make SAF more attractive for profit or social welfare maximization? As far as we know, no existing study has answered these questions yet. This paper aims to bridge this gap by building a simple model to investigate how airlines choose between SAF and carbon offsets to fulfil their decarbonization duties, and the discrepancy between the profit maximizing and social welfare maximizing decisions. We first consider the benchmark case when SAF and carbon offset are treated equally, then explore the scenario with a SAF multiplier.

The contribution of this paper is two-fold. Theoretically, it is the first to investigate how airlines and governments choose between SAF and carbon offsets, providing a framework to analyze the decisions of airlines to adopt SAF with offset being an equal or unequal alternative. Innovation in model formulation includes incorporating specific features of SAF, such as production economies and potential multiplier policies. Practically, this paper reveals the effectiveness of a CORSIA-like policy in promoting SAF production and adoption. It suggests that while aggressively promoting SAF quotas, such as the ambitious policies in ReFuelEU (an EU initiative aimed at increasing the use of SAF), is important, it may be inefficient if SAF prices remain uncompetitive. This insight can assist regulators in designing more effective policies to promote SAF and reduce aviation emissions.

The rest of the paper is organized as follows. Section 2 provides literature review while Section 3 sets up the model. Section 4 focuses on analytical results. Section 5 offers concluding remarks.

2. Literature review

There are three distinct streams of literature relevant to this paper. The first stream focuses on the economic impacts of SAF, the second delves into CORSIA, and the third examines the credit multipliers

[3] For a fuel to be CORSIA-eligible, it must undergo certification through approved mechanisms based on criteria established by ICAO. Specifically, CORSIA-eligible fuel generates at least 10 % fewer greenhouse gas emissions throughout its lifecycle compared to conventional fossil-based Jet A fuel. Additionally, the feedstock cannot come from land converted after January 1, 2008, if it was previously primary forest, wetlands, or peatlands, and must not degrade those areas.

[4] SAF can be broadly classified into two types based on the nature of feedstocks. One type is made from renewable biomass or waste-based feedstock that has a lower life-cycle carbon intensity than conventional petroleum-based fuel. Another type of SAF is e-SAF or Power to Liquid (PtL), produced by combining hydrogen—derived from water using renewable electricity through electrolysis—with carbon extracted from the atmosphere or industrial waste gas.

[5] It should be noted that the range of carbon reduction percentages for different SAF pathways can vary widely. According to Kahn et al. (2023), 14 pathways are capable of a high reduction in CO2 emissions by 68–95 %, six pathways offer a medium reduction by 36–67 %, and three pathways provide a low reduction of less than 35 %. These figures represent the potential life-cycle emissions reductions when compared to conventional jet fuels. It's important to note that these reductions are contingent upon the specific feedstock, production process, and other factors related to the SAF pathway. SAF also offers advantages as a drop-in fuel that blends directly with fossil jet fuel without needing special infrastructure or equipment changes. Moreover, it has higher fuel density and can reduce particulate matter emissions by up to 90 % of and sulfur emissions up to 100 % (Karantzavelou, 2020).

[6] Some SAF production pathways, such as Hydroprocessed Esters and Fatty Acids (HEFA), have already achieved a high Technology Readiness Level (TRL). This means they are relatively mature and close to or already in commercial use, and their cost reduction potential is largely dependent on innovations and improvements in feedstock sourcing and processing.

mechanism in the promotion of green technology.

First and foremost, few studies have examined the economic aspects of SAF. Most existing research on SAF estimates its future demand and its role in curbing aviation emissions (e.g., Kousoulidou and Lonza, 2016; Chiaramonti, 2019). Smith et al. (2017) identify the main drivers and barriers for a profitable SAF industry in the U.S. Pacific Northwest based on personal interviews. They argue that airlines, as the main purchasers of SAF, should lead industry development. Few studies have explored SAF-related policies. Timilsina et al. (2011) suggest that a carbon tax on fossil fuels, with some revenue used for biofuel subsidies, would effectively promote biofuel adoption in aviation. Norberg (2014) finds that the technical hurdles of incorporating SAF into the fuel distribution system are manageable. However, to reduce emissions in aviation, a larger-scale quota requirement must be implemented. Winchester et al. (2015) assess the economic and emissions effects of the Federal Aviation Administration's renewable jet fuel goal in the U.S. commercial aviation. They find that the goal has a minor impact on aviation operations and emissions. Wise et al. (2017) suggest that a carbon price would significantly affect the aviation industry, but without viable alternatives to petroleum-based jet fuel, mitigating emissions would be challenging and could hinder air travel demand. Qiu et al. (2020) emphasize that increasing biojet fuels usage can lower aviation's carbon intensity without significantly affecting bioenergy consumption in other sectors. However, they also caution that using carbon tax revenue to promote fossil fuel savings and carbon emissions reduction depends on conditions like low transaction costs and a substantial price gap between conventional jet fuel and biojet fuel. Jiang and Yang (2021) compare a carbon tax and a SAF quota for reducing aviation emissions. They find a carbon tax more efficient and flexible, promoting optimal SAF use without constraints, while a SAF quota can be powerful for significantly reducing emissions. Zheng et al. (2024) compare the environmental and welfare impacts of subsidy and quota policies for SAF. They show that subsidies are better for consumer surplus, airline profits, SAF blender profit, and social welfare, provided traditional aviation fuel is inexpensive and emission regulations are stringent.

The literature on CORSIA is also scarce. Scheelhaase et al. (2018) compare EU ETS and CORSIA, two market-based measures to limit aviation CO2 emissions. They find that EU ETS is more effective and ambitious in reducing emissions but imposes higher costs on airlines. Additionally, these measures may cause conflicts or overlaps in some regions.[7] Zheng et al. (2019) develop a theoretical model that compares two types of voluntary carbon offsets schemes: a Chicago Climate Exchange (CCX)-style market and an over-the-counter (OTC) market. They suggest that in a CCX-style market, airlines do not benefit from alliances, as they face a common offset price and compete on ticket prices. Conversely, in an OTC market, airlines may benefit from alliances by bargaining collectively for lower offset prices and increasing profits. Prussi et al. (2021) describe the key features of CORSIA and discuss its challenges, including double counting and the lack of a comprehensive framework for evaluating the effectiveness of carbon offsets projects. They conclude that while CORSIA is an important step in reducing emissions, more action is needed to address the aviation's contribution to climate change. He (2022) presents a time-sensitive graph model to analyze international negotiations with different action durations for negotiators. The model is applied to an air carbon negotiation involving the EU, major developing countries, and the US under CORSIA. The equilibrium achieved after June 2020 suggests that the EU ETS Monitoring, Reporting and Verification (MRV) Baseline could be adjusted by the end of the Pilot Phase. Liao et al. (2023) compare how different countries are expected to offset their carbon emissions from international flights under CORSIA and four other fairness-based principles. They find that CORSIA is inequitable, favoring some countries over others by neglecting historical responsibility, ability to pay, and per capita emissions.

Literature on CORSIA often mentions the role of SAF (e.g., Prussi et al., 2021). However, the discussion regarding whether and how CORSIA should incentivize the production and usage of SAF is lacking. Chao et al. (2019) show that a CORSIA-type policy could increase the demand and production of SAF but reduce air travel growth by raising airfares. They also identify conventional aviation fuel price and carbon price growth rates as key factors in determining if the policy would reduce emissions. Substantial investment and support from governments, airlines, and stakeholders are needed to maximize SAF's ability to lower emissions.

Credit multipliers are mechanisms that amplify the impact of specific policies or actions to incentivize them. Used in various contexts like environmental policies, financial systems, and economic development, their primary purpose is to encourage certain behaviors or investments by providing additional benefits. In environmental policies, credit multipliers enhance the attractiveness of eco-friendly actions, incentivizing environmentally responsible behaviors. Renewable Portfolio Standards (RPS), also known as Renewable Electricity Standards (RES), are well-studied policies involving credit multipliers. They aim to increase the use of renewable energy sources for electricity generation. Lips (2018) investigates credit multipliers within RPS, which incentivize specific renewable energy sources by awarding more (or fewer) renewable energy certificates (REC) for their electricity production. He finds mixed results from 21 states and the District of Columbia, with some states seeing increased development of target technologies while others do not. Kim and Tang (2020) discover that price-based REC multipliers applied to less mature technologies do not effectively enhance diversity in the Renewable Energy (RE) market.[8] Despite receiving additional RECs, utilities may still hesitate to purchase electricity from these technologies due to their persistently high costs. Additionally, price-based credit multipliers on competitive technologies can indirectly benefit less competitive technologies. This interplay between different technology-specific incentives requires careful consideration when designing effective RPS policies. Rountree (2019) investigates stakeholder perceptions regarding the evolution of specific policy design features within Nevada's RPS. Rountree finds that the credit multiplier for solar photovoltaic (PV) systems undermined policy goals, by distorting market signals by exaggerating solar PV contributions. Consequently, the multiplier conflicted with the goal of increasing renewable energy generation and raised equity concerns by favoring some projects over others. Fischlein and Smith (2013) explore patterns in RPS policy design and their impact on policy outcomes, focusing on utility compliance. Their findings indicate that policy designs with exceptions to the RPS goal are linked to diminished policy responses. Utilities may strategically leverage multipliers to generate renewable energy types for additional credits or to produce renewable energy within the state boundaries for extra credit. Wiser et al. (2011) study state-level RPS programs in the United States, focusing on solar energy. They find that solar set-asides, which allocate a specific share of the RPS goal to solar energy, are more popular and effective than credit multipliers. Set-asides offer greater certainty in solar energy production, driving market growth in several states. In contrast, while solar credit multipliers are promising, they lack comparable success due to limited operational experience. In summary, the REC literature presents mixed results regarding the effectiveness of credit multipliers in promoting renewable energy technologies. Specifically, while credit multipliers have led to significant growth in some cases, they have not notably increased renewable energy development in others. This study contributes to the existing research by analytically confirming these diverse outcomes and

[7] Since the publication of Scheelhaase et al. (2018), changes in both schemes may affect their comparison. EU ETS will apply for intra-European flights (including departing flights to the United Kingdom and Switzerland), while CORSIA will apply to extra-European flights to and from third countries participating in CORSIA ('clean cut') from 2022 to 2027.

[8] While standard RECs are traded based on market conditions and can have variable prices, price-based RECs offer more predictable pricing, often linked to specific economic factors or agreements. This distinction can be important for entities looking to manage their renewable energy investments and compliance costs more effectively.

identifying the conditions under which multipliers can either enhance or diminish the attractiveness of such sustainable technologies.

3. Model setting

We consider a market that needs to abide by CORSIA, and assume that the collective utility of passengers in this market adopts the classic quadratic form (e.g., Singh and Vives, 1984):

$$U = \alpha Q - \frac{1}{2}Q^2 \tag{1}$$

where Q is the total air traffic volume in this market. From Eq. (1) we can derive the inverse demand function of the market:

$$P = \alpha - Q \tag{2}$$

Next, we will consider a few different scenarios: a monopoly airline market and an oligopoly airline market when SAF and carbon offset credits are treated equally, as well as these markets when a SAF multiplier is applied.

3.1. Monopoly market

We first consider one airline that monopolizes the market. This airline bears two different types of cost. The first is the regular operating cost, which is assumed to be 0 without loss of generality. The second is related to emissions and the requirement of CORSIA. The airlines can purchase either offset credit from other sectors or SAF to fulfil such requirement.[9] We assume that the per unit cost of carbon offset credits is exogenously given at c, as these offset credits are mainly from outside the aviation sector that the airlines are not able to effectively influence. However, the cost of SAF exhibits economies of scale, because SAF is within the aviation sector with airlines being its main customers. In particular, the per unit cost of SAF is $1 - \delta Q$, where δ is the economies of scale of SAF. It implies that the larger the total production of SAF, the lower the cost. Furthermore, to reflect the fact that the carbon offset credit is cheaper than SAF, we assume that $c < 1$.

Under CORSIA, the airline can purchase either carbon offset credits or SAF to fulfil their decarbonization obligation.[10] When the airline chooses to purchase offset credits, its profit function is:

$$\Pi = (P - c)Q \tag{3}$$

When the airline chooses to purchase SAF, its profit function is:

$$\Pi = [P - (1 - \delta Q)]Q \tag{4}$$

It should be noted that this model may not completely correspond to actual scenarios, especially concerning airlines' lag in offsetting excess emissions. Additionally, exploring the parameter dynamics with unchanged traffic volume would offer an interesting study, albeit from a different perspective than our current one.

Moving forward, let's discuss social welfare functions. In this case, we will utilize the utilitarian social welfare function as proposed by Gruber (2010). This function calculates social welfare by adding up individual utilities, which is equivalent to the combined surplus of consumers, companies, and the government, and then subtracting the social cost. Here we also consider the fact that neither SAF nor carbon offsets allow completely cutting all emissions, as discussed in the introduction. When the airline chooses to purchase carbon offset credits, the social welfare function is:

$$SW = \alpha Q - \frac{1}{2}Q^2 - cQ - \theta_O eQ \tag{5}$$

where e denotes the emissions associated with each passenger, while θ_O denotes the percentage of emissions that cannot be abated by the carbon offsets.

Meanwhile, when the airline decides to purchase SAF, the social welfare function is:

$$SW = \alpha Q - \frac{1}{2}Q^2 - (1 - \delta Q)Q - \theta_S eQ, \tag{6}$$

where θ_S denotes the percentage of emissions that cannot be abated by SAF. In order to make the two strategies comparable, we further assume that $\theta_S = \theta_O$.

3.2. Oligopoly market

Now we extend our analysis to an oligopoly market with n homogeneous airlines, which are competing with each other and all need to abide by CORSIA. In this case, $Q = \sum_n q_i$, where q_i is the traffic volume of Airline i, with $i = 1, 2 \dots n$. Again, we consider that carbon offset credits and SAF contribute equally to fulfil the airlines' decarbonization obligation under CORSIA. When all airlines purchase offset credits, the profit function of Airline i is:

$$\pi_i = (P - c)q_i \tag{7}$$

When the airlines purchase SAF, the profit function of Airline i is:

$$\pi_i = \left[P - \left(1 - \delta\sum_n q_i\right)\right]q_i \tag{8}$$

When airlines choose to purchase carbon offset credits, the social welfare function is:

$$SW = \alpha\sum_n q_i - \frac{1}{2}\left(\sum_n q_i\right)^2 - c\sum_n q_i - \theta_O e\sum_n q_i \tag{9}$$

Meanwhile, when airlines decide to purchase SAF, the social welfare function is:

$$SW = \alpha\sum_n q_i - \frac{1}{2}\left(\sum_n q_i\right)^2 - \left(1 - \delta\sum_n q_i\right)\sum_n q_i - \theta_O e\sum_n q_i \tag{10}$$

3.3. SAF multiplier

Next, we consider the case where SAF and carbon offset credits are no longer equivalent for airlines to abide by CORSIA. Specifically, a multiplier is given to SAF, meaning that the usage of every unit of SAF will be counted more than its real carbon-cutting contribution.

[9] It should be noted that for simplicity, we assume that airlines are responsible for mitigating all emissions produced by their operations. However, in practice, this isn't entirely accurate. Under the guidelines of CORSIA, airlines are only obligated to utilize SAF (or other CORSIA eligible fuels) or engage in offsetting practices to manage their emissions when they surpass a predetermined benchmark. Notably, the ICAO Council agreed to use 2019 emissions as CORSIA's baseline for the period of 2021–2023, and 85 % of 2019 emissions as the baseline from 2024 until the end of the scheme in 2035. Furthermore, the aviation sector has pledged to achieve net-zero carbon emissions by the year 2050. Essentially, our analysis reflects the industry's overarching ambition for carbon neutrality in the long run.

[10] It's important to recognize that airlines have the practical option of combining both strategies to address emissions. However, within our analytical model, such a combination is not feasible due to cost considerations that make one strategy more economically advantageous, thus predominant. The implementation of SAF mandates in various countries, such as the existing mandates for flights from EU airports and the forthcoming mandate in Singapore starting in 2026, could incentivize airlines to employ a dual-strategy approach. Nevertheless, this scenario holds less relevance for our study. In particular, our results indicate that airlines will opt for SAF exclusively when it is more cost-effective than carbon offsets, otherwise, they will meet the SAF mandate and use carbon offsets for remaining emissions if offsets are cheaper. For an in-depth analysis of the SAF mandate policy, Jiang and Yang (2021) is a valuable resource.

In this case, when all airlines purchase offset credits, the profit function of Airline i and the social welfare function are still Eqs. (7) and (9), respectively. However, when the airlines purchase SAF, the profit function of Airline i is instead:

$$\pi_i = \left[P - \tau\left(1 - \delta\sum_n \tau q_i\right)\right]q_i \tag{11}$$

where τ is the reciprocal of the SAF multiplier. In other words, the SAF multiplier is $1/\tau$. With this multiplier in place, an airline with traffic volume q_i will only need to purchase τq_i equivalent amount of SAF to fulfil its CORSIA obligation. Since $1/\tau > 1$ by definition, we should have $0 < \tau < 1$. There are two aspects to the effect of τ on the cost function $\tau(1 - \delta\sum_n \tau q_i)$. First, since the airline only need to purchase τq_i amount of SAF, the SAF cost per passenger is changed to $(1 - \delta\sum_n \tau q_i)$. Second, this cost should only be applied to those τq_i amount of passengers. Therefore, the final cost is $(1 - \delta\sum_n \tau q_i)$ multiplied by τ.

Meanwhile, the social welfare function in this case is:

$$SW = \alpha\sum_n q_i - \frac{1}{2}\left(\sum_n q_i\right)^2 - \left(1 - \delta\sum_n \tau q_i\right)\sum_n \tau q_i - e\sum_n (1-\tau)q_i - \theta_O e\sum_n \tau q_i \tag{12}$$

where e is the unit social cost of GHG emissions from the airlines. It should be noted that with the SAF multiplier, some of the airlines' GHG emissions will not be offset, thus the relevant cost will appear in the social welfare function.

3.4. Interaction between SAF multiplier and SAF tax credit

Finally, we investigate the case where there exist other policies to promote the usage of SAF. In particular, we consider the tax credits given to airlines in the US following the Sustainable Skies Act 2021.

Again, when all airlines purchase offset credits, the profit function of Airline i and the social welfare function are still eqs. (7) and (9), respectively. However, when the airlines purchase SAF, the profit function of Airline i is instead:

$$\pi_i = \left[P - \tau\left(1 - \delta\sum_n \tau q_i - s\right)\right]q_i \tag{13}$$

where s is the tax credit given the airline for the use of SAF. It should be pointed out that such tax credit plays a similar role as subsidy in analytical models.

Since the tax credit is a type of internal transfer for the economic system, it will not appear in the social welfare function, which is still given by eq. (12).

4. Analytical results

4.1. Monopoly market

The equilibrium results when the monopoly airline adopts the two strategies can be summarized in the following Table 1.

Comparing the equilibria under the two strategies (purchasing carbon offset credits vs. purchasing SAF), we can reach a few conclusions, which have been summarized as propositions below. We first investigate how costs affect the relative attractiveness of the two strategies.

Proposition 1. When the unit costs of SAF and carbon credits are equal, airlines profit less but emit more when using SAF compared to carbon credits. Social welfare is higher with SAF only if the uncompensated emission rate is sufficiently low ($\theta_O < \frac{2\alpha - c - 1}{4e}$).

The proofs for Proposition 1 and the subsequent propositions are all located in the Appendix. Proposition 1 is somewhat surprising, as it suggests that even when the unit costs are the same, SAF is still disadvantaged compared with carbon offset credits, with respect to both airline profit and uncompensated carbon emissions. This is due to the cost structures of the two alternatives. Carbon offset credits have an exogenously cost, while SAF benefits from economies of scale and decreasing marginal costs. Such economies of scale have weakened the airline's market power. When planning a price hike, the airline must consider both traffic loss and the resulting cost increase. The airline would lose more from raising prices when purchasing SAF. Therefore, the airline will need a lower unit cost of SAF to make the same level of profit. Moreover, the equilibrium traffic volume is higher when airlines opt for SAF, leading to higher uncompensated carbon emissions. However, the economies of scale in SAF production can enhance social welfare more effectively when the uncompensated emissions rate is low. Therefore, when the unit costs are the same, using SAF results in higher social welfare. Conversely, a higher uncompensated emission rate amplifies the carbon emission disadvantage of SAF. Larger economies of scale in SAF production are required for it to be more socially beneficial. However, in the reality, some passengers and airlines have shown preference for SAF over carbon offset credits (Jennifer, 2022). Besides, SAF has been shown to have other social benefits, including the reduction of particulate matter and sulfur emissions (Karantzavelou, 2020), meaning that all things being equal, the usage of SAF may still lead to a higher social welfare level than the usage of carbon offsets.

The threshold of the uncompensated emission rate $\frac{2\alpha - c - 1}{4e}$ has certain economic meanings. To begin with, this threshold increases with the market size. A larger market size equally affects traffic volume for airlines purchasing SAF and carbon offsets, resulting in identical impacts on carbon emissions under both strategies. However, when the costs are the same, an increase in market size leads to a greater rise in passenger utility when airlines opt for SAF. This is because the traffic volume under the SAF strategy is higher, enhancing the effect of market size on utility. Consequently, a larger market size has a greater positive impact on passenger utility when airline purchasing SAF, while the negative emissions effects remain the same. This lowers the requirement for the uncompensated emission rate, meaning a larger rate is sufficient for SAF to be socially preferable.

The threshold decreases with the unit cost of carbon offsets. An increase in cost reduces the traffic volume under both strategies, with a more significant decline for SAF. The loss in passenger utility from the sharp drop in traffic volume outweighs the benefit from reducing emissions. Consequently, the negative impact of rising cost on social welfare is greater for SAF than for carbon offsets. This increases the requirement for the uncompensated emission rate, meaning a smaller rate is needed for SAF to be socially preferable.

The threshold also decreases with the social cost of emissions per passenger. When the costs of SAF and carbon offsets are equal, the carbon emissions when the airline purchases SAF are higher. If the unit emissions cost is higher, a lower uncompensated emission rate is necessary to reduce the emission disadvantage of SAF, resulting in a more favorable outcome for social welfare.

Table 1
Equilibrium traffic, airline profit, social welfare and emissions levels in a monopoly market.

	The airline purchases carbon offset credits	The airline purchases SAF
Q	$\frac{\alpha - c}{2}$	$\frac{\alpha - 1}{2(1-\delta)}$
Π	$\frac{(\alpha - c)^2}{4}$	$\frac{(\alpha - 1)^2}{4(1-\delta)}$
SW	$\frac{3(\alpha - c)^2 - 4\theta_O e(\alpha - c)}{8}$	$\frac{(\alpha - 1)^2(3 - 2\delta) - 4(1-\delta)e(\alpha - 1)\theta_O}{8(1-\delta)^2}$
E	$\frac{\theta_O e(\alpha - c)}{2}$	$\frac{\theta_O e(\alpha - 1)}{2(1-\delta)}$

Proposition 1 has important policy implications, suggesting that SAF is a less attractive alternative for airline decarbonization from an economic perspective. To achieve the same profit level, SAF must lower its unit cost below that of carbon offsets. It needs to go even further to achieve a lower cost base. This is a daunting task considering that SAF is currently a few times more expensive than carbon offset credits. It explains why airlines are generally lukewarm toward the mass utilization of such fuel. In other words, SAF is badly in need of supportive policies from the government to really take off. Without such policies, SAF would struggle to become a viable option for airlines, especially with the availability of inexpensive alternatives like carbon offsets. Additionally, even with a significant reduction in the cost of SAF to match that of carbon credits, prudence remains paramount. In this case, the adoption of SAF still does not guarantee lower carbon emissions, which is contingent upon the effectiveness of SAF in carbon abatement. If carbon abatement is insufficient or if carbon reduction is a pivotal goal for policymakers, SAF may not meet the objectives of a social planner. Thus, without strong carbon mitigation capabilities, SAF's role in achieving environmental goals remains uncertain.

Next, we dive deeper into comparing the two decarbonization alternatives in terms of airline profit and social welfare. We can obtain the following proposition.

Proposition 2. When the uncompensated emission rate is high ($\theta_O > \frac{c+c^2-\alpha-3c\alpha+2\alpha^2}{-4e+4e\alpha}$), achieving greater social welfare with SAF compared to carbon offset credits requires substantially strong economies of scale in SAF production. This requirement is more stringent than the economies of scale needed to enhance airline profitability.

It is straightforward to know that the traffic volume under SAF purchase is higher than that under carbon credit purchase when the airline profit is the same. In this case, the consumer surplus will naturally be higher under SAF purchase. However, larger traffic volume also lead to more uncompensated carbon emissions, which complicates the assessment of total social welfare. To equalize social welfare between SAF and carbon credits amidst significant uncompensated emissions, it is imperative to enhance the economies of scale in SAF production further. Only then can SAF become a contender for airline decarbonization strategies, balancing economic and environmental considerations.

The policy implications of Proposition 2 are relevant to those of Proposition 1. In particular, it shows that while making SAF commercially attractive for airlines is challenging, it may be even more demanding for it to be a socially preferable option. Ignoring other social benefits of SAF, developing SAF may be hard to justify without assurance of its production scalability. In other words, CORSIA may need to be conservative in prioritizing SAF usage over carbon offsets, as while there are some technological pathways for SAF production, none has demonstrated significant economies of scale. That being said, the current production and utilization of SAF are so limited that we lack sufficient information about these economies. Relevant studies are also lacking at the moment. These all require immediate attention from the policymakers.

In the next subsection, we will examine the impact of airline competition on our analysis and discussion.

4.2. Oligopoly market

In the case of an oligopoly market, we can also derive the equilibrium levels of traffic, airline profits, social welfare and emissions, which have been summarized in the following Table 2.

The main purpose of this subsection is to figure out the role of airline competition in the comparison between SAF and carbon offset credits. This has been achieved by analyzing the comparative statics with respect to n. And the conclusions are summarized in the following proposition.

Proposition 3. Increased airline competition lowers the required economies of scale for SAF production to be cheaper or more socially beneficial than offset credits. Airline competition does not affect the economies of scale threshold needed for airlines to achieve higher profits and lower uncompensated emissions with SAF over carbon offset credits.

Proposition 3 discusses the impact of airline competition on the cost, airline profit, carbon emission and social welfare comparisons between SAF and carbon offsets. In terms of cost, more airline competition leads to higher total traffic, increasing SAF usage. This lowers the unit cost of SAF, reducing the need for high economies of scale to match the cost of carbon offset credits. In terms of social welfare, when airlines use SAF, the equilibrium air total traffic is higher, assuming the same profit level. This gap widens with more competition. Higher traffic also significantly reduces the cost of SAF, mitigating the disadvantages related to carbon emissions for SAF. Therefore, lower economies of scale are sufficient to enhance social welfare when airlines use SAF. In terms of airline profit and carbon emission, competition reduces the economies of scale required for cheaper SAF. However, it raises the threshold for airlines to achieve the same profit as with carbon offsets due to increased positive externalities. These effects balance each other out. The comparison of carbon emissions depends on total traffic volume under each strategy, influenced by competition but determined by SAF production economies of scale and carbon offset cost.

Proposition 3 is very important, as it provides a few policy lessons for regulators. First, a higher level of airline competition is expected to level the playing field for SAF and carbon offsets. The more airlines use SAF, the faster SAF price can be reduced to match carbon offsets. Second, a higher level of airline competition would not make SAF more attractive to airlines, thus it is not helpful for the SAF deployment. Third and most importantly, higher airline competition would make SAF more favorable for the policymakers. Combining the first and last policy implications leads to an interesting conclusion: the situation in which SAF achieves cost competitiveness with carbon offsets coincides with when SAF is more socially beneficial than carbon offsets. Both require the scale economy of SAF production to be sufficiently large, while airline competition will close the gap between the two. Therefore, regulators might consider a more accommodating approach in competitive airline markets, as lower SAF production costs could also indicate that SAF is a superior decarbonization option compared to carbon offsets.

4.3. SAF multiplier

In this subsection, we focus on the hypothetical situation when a multiplier is given to SAF usage. We summarize the market equilibria under this situation in the following Table 3.

The column for the case when the airlines purchase carbon offset credits is exactly the same in Tables 2 and 3, because a SAF multiplier does not affect the carbon offsets market. In other words, we only need

Table 2
Equilibrium traffic, airline profit, social welfare and emissions levels in an oligopoly market.

	The airlines purchase carbon offset credits	The airlines purchase SAF
q_i	$\frac{\alpha-c}{n+1}$	$\frac{\alpha-1}{(n+1)(1-\delta)}$
π_i	$\frac{(\alpha-c)^2}{(n+1)^2}$	$\frac{(\alpha-1)^2}{(n+1)^2(1-\delta)}$
SW	$\frac{n(n+2)(\alpha-c)^2}{2(n+1)^2}-\frac{\theta_O en(\alpha-c)}{n+1}$	$\frac{n(n+2-2\delta)(\alpha-1)^2}{2(n+1)^2(1-\delta)^2}-\frac{\theta_O en(\alpha-1)}{(n+1)(1-\delta)}$
E	$\frac{\theta_O en(\alpha-c)}{n+1}$	$\frac{\theta_O en(\alpha-1)}{(n+1)(1-\delta)}$

to compare the last columns of the two tables to figure out the impact of the multiplier. We first look at the impact of the multiplier on airline profit and reach the following proposition.

Proposition 4. A moderate SAF multiplier (relative to the market size and the SAF production scale economies) decreases the profit of the airlines when they purchase SAF.

Proposition 4 suggests that a SAF multiplier does not always improve the attractiveness of SAF for the airlines. This is due to the trade-off discussed in the introduction section: while the multiplier reduces airlines' obligations and decarbonization costs, it prevents SAF production growth. In fact, a larger multiplier amplifies the effects on both ends. Therefore, whether a SAF multiplier is good or bad for the airlines depends on three factors, i.e., the magnitude of the multiplier, the market size and the level of the scale economies of SAF production. The larger the latter two factors, the more important the production scale for airlines. This makes it more likely that a SAF multiplier, especially a moderate one, decreases instead of increases the airlines' profits.

The conclusion of Proposition 4 is important, as it points out the conditions under which a SAF multiplier fails in a CORSIA-type framework. A few policy lessons can be drawn from this proposition. First, increasing the magnitude of the SAF multiplier may not be the right strategy. Starting from a large multiplier and gradually decreasing it may be more suitable in many cases. Second, a multiplier is not always necessary and beneficial. There multiplier is useful in two situations: either when the market size is small or when the scale economies of SAF production are small. However, in these cases, it may be questionable whether promoting SAF over carbon offsets is justified. Therefore, the effectiveness of the SAF multiplier as a policy tool may need a more comprehensive evaluation.

In addition, we find that when the economies of scale in SAF production are sufficiently large, an increase in the SAF multiplier will reduce carbon emissions. Our analysis indicates that under moderate economies of scale in SAF production, for small values of uncompensated emission rate ($\theta_O < \frac{\alpha-1}{\alpha}$), a decrease in SAF multiplier can lead to both a reduction in emissions and an increase in airline profit (see the overlap region in Fig. 1, we let $R_\delta = \frac{(-\alpha+\tau)(1+(\theta_O-1)\alpha)}{\tau((2+(\theta_O-1)\tau)\alpha-\tau)\alpha}$ in both Figs. 1 and 2). Conversely, if the uncompensated emission rate is high ($\theta_O > \frac{\alpha-1}{\alpha}$), an increase in the multiplier can be beneficial in both emissions and airline profit (see the gap between the two regions in Fig. 1).

In this section, we categorize emissions into two parts: carbon emissions that should have been offset but were not, and carbon emissions that were not fully offset by SAF. Given that the SAF multiplier affects total traffic and is influenced by economies of scale in SAF production, analyzing its impact on emissions is quite complex. Therefore, we will not delve into further analytical details about this conclusion here.

Next, let's look at social welfare. By comparing the impacts of the multiplier on social welfare with those on airline profit, we can reach the following proposition.

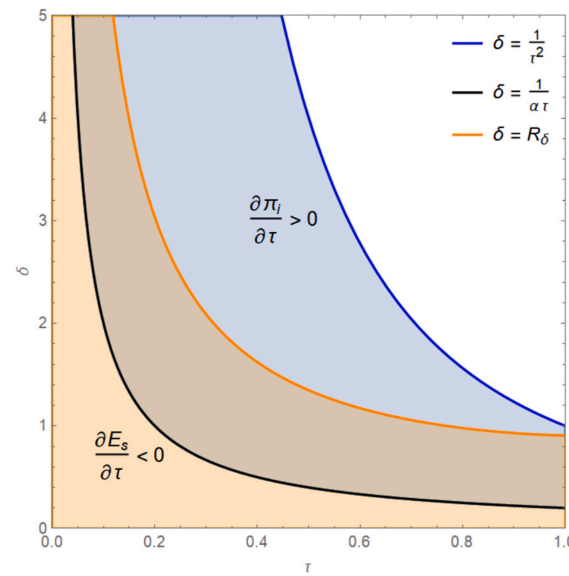

Fig. 1. The impact of multiplier on profit and emissions when $\theta_O < \frac{\alpha-1}{\alpha}$.

Proposition 5. When the unit emission cost is either low, or high with a small uncompensated emission rate, enhancing social welfare with a small SAF multiplier is more challenging than increasing airline profitability.

The intuition behind Propositions 5, 2, and 3 is that it is more challenging for SAF to be socially beneficial than to be more profitable. In this proposition, a small SAF multiplier encourages only limited SAF usage. If the social cost of uncompensated emissions is low, the positive impact of the SAF multiplier becomes less clear. This makes it harder to increase social welfare.

Combining Propositions 4 and 5, we find that a SAF multiplier may not effectively promote SAF adoption and development, mainly due to the existence of the production economies of scale. More thought-after and fine-tuned policies may be needed if the regulators want to give additional push to SAF usage under a CORSIA-type policy framework.

4.4. Interaction between SAF multiplier and SAF tax credit

Next, we examine the scenario where the SAF multiplier is implemented alongside tax incentives for utilizing SAF. The equilibrium outcomes are derived as follows (See Table 4).

Proposition 6. The SAF tax credit enhances the benefit of the SAF multiplier. When the subsidy is large enough ($s > 1 - \alpha\delta\tau$), the SAF multiplier always increases the profit of the airlines when they purchase SAF.

Proposition 6 concludes that a substantially large SAF tax credit can enhance the appeal of the SAF multiplier. Although a multiplier may not always increase the appeal of SAF for airlines, introducing a SAF tax credit can effectively address this issue. This efficacy stems from the tax credit's promotion of SAF usage, neutralizing the SAF multiplier's deterrent effect on SAF adoption. Consequently, when the tax credit is substantial, it overturns the inhibitory influence of the SAF multiplier. In such instances, an increase in the multiplier increases the profitability for airlines opting for SAF. However, it is important to acknowledge that this scenario would also lead to increased traffic and, consequently, higher total emissions.

5. Discussion and conclusions

This paper presents a model to explore how airlines decide between

Table 3
Equilibrium traffic, airline profit, social welfare and emissions levels in an oligopoly market with SAF multiplier.

	The airlines purchase carbon offsets credits	The airlines purchase SAF
q_i	$\frac{\alpha-c}{n+1}$	$\frac{\alpha-\tau}{(n+1)(1-\delta\tau^2)}$
π_i	$\frac{(\alpha-c)^2}{(n+1)^2}$	$\frac{(\alpha-\tau)^2}{(n+1)^2(1-\delta\tau^2)}$
SW	$\frac{n(n+2)(\alpha-c)^2}{2(n+1)^2} - \frac{\theta_O en(\alpha-c)}{n+1}$	$\frac{n(n+2-2\delta\tau^2)(\alpha-\tau)^2}{2(n+1)^2(1-\delta\tau^2)^2} - \frac{n(\alpha-\tau)(1-\tau+\tau\theta_O)e}{(n+1)(1-\delta\tau^2)}$
E	$\frac{\theta_O en(\alpha-c)}{n+1}$	$\frac{n(\alpha-\tau)(1-\tau+\tau\theta_O)e}{(n+1)(1-\delta\tau^2)}$

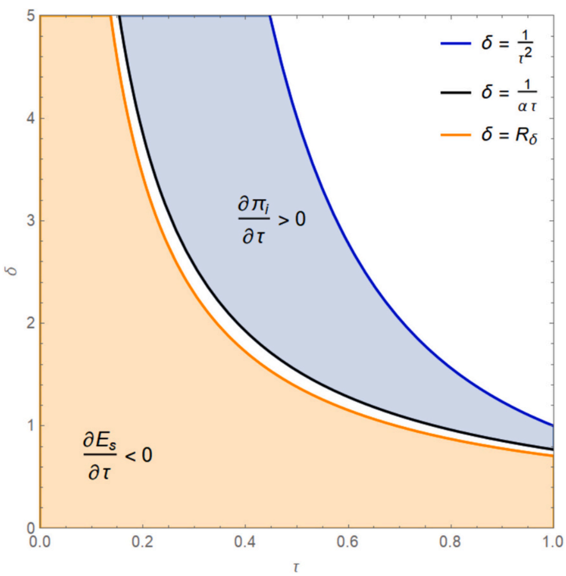

Fig. 2. The impact of multiplier on profit and emissions when $\theta_O > \frac{\alpha-1}{\alpha}$.

buying SAF or carbon offset credits to meet decarbonization obligations, given that both are treated equally in CORSIA. We also analyze the role of airline competition and the differences between airlines' profit-maximizing choices and those that promote social welfare. We obtain the following conclusions. First, for airlines to choose SAF, the unit cost of SAF must be lower than that of carbon credits to maintain equal profit. Second, when the uncompensated emissions rate is high, SAF must have higher economies of scale to be a better social option, compared to be more profitable. Third, airline competition affects the economies of scale required for SAF to be cheaper and more attractive for society. However, airline competition does not affect the economies of scale requirement needed for airlines to make higher profits and carbon emissions when choosing SAF. Last, a moderate SAF multiplier can decrease airlines' chance of obtaining higher profits when purchasing SAF, while the same conclusion also holds for social welfare.

To fulfil their offset duties, airlines can employ a combination of both carbon credits and SAF. The two strategies in our analytical framework represent the extreme cases within the airlines' range of choices. In reality, it's rare for an airline to rely solely on one strategy. From an economic analysis standpoint, one strategy will inevitably be more cost-effective than the other. The reasons behind airlines' adoption of a mixed strategy are often complex. For instance, a global deficiency of SAF feedstocks makes it nearly impossible for an airline to depend entirely on SAF for its offset. Our analytical framework does not specifically account for these factors. We can logically infer that if an airline is required to use SAF to offset a certain percentage of its carbon emissions (like the EU's SAF mandate), a profit-maximizing airline would use SAF up to the required level and carbon credits for the rest due to the higher price of SAF. Conversely, if SAF is cheaper than carbon offsets, and its supply is unlimited, the airline will use SAF exclusively.

These findings have important implications for policymakers developing decarbonization policies for aviation. Since airlines base their choice between SAF and carbon offsets on cost, substantially reduce the cost of SAF is essential to encourage its adoption by airlines. However, the results also suggest that policies must be carefully designed to promote social welfare, not just maximize airline profits. Furthermore, the finding that economies of scale are crucial for making SAF the socially better option highlights the need for policymakers to support larger-scale SAF production. This could involve measures such as funding research and development, providing tax incentives, or implementing regulations to encourage SAF production. Finally, policymakers may need to consider alternative measures, such as emissions trading or carbon pricing, instead of multipliers for effective airline decarbonization. Overall, this study s valuable insights for policymakers seeking to incentivize the adoption of more SAF and reduce aviation's carbon footprint.

Our model is simplified for mathematical tractability. Notably, we have not accounted for SAF price volatility. Including this uncertainty could reveal significant impacts. Furthermore, our model does not reflect the diversity and technical nuances of SAF. The industry recognizes several SAF production pathways, indicating that SAF standards are still evolving. Addressing these within our analytical framework poses challenges but also offers substantial rewards. Finally, our paper assumes airlines are homogeneous, unlike the real world where airlines vary in emissions reduction. Particularly, airlines with higher occupancy rates and larger fleets of high-emission aircraft have higher per-unit emissions, a factor that could provide deeper insights when considered.

Table 4
Equilibrium traffic, airline profit and social welfare levels in an oligopoly market with SAF multiplier and tax credit.

	The airlines purchase carbon offsets credits	The airlines purchase SAF
q_i	$\frac{\alpha-c}{n+1}$	$\frac{\alpha-\tau+s\tau}{(n+1)(1-\delta\tau^2)}$
π_i	$\frac{(\alpha-c)^2}{(n+1)^2}$	$\frac{(\alpha+(s-1)\tau)^2}{(n+1)^2(1-\delta\tau^2)}$
SW	$\frac{n(n+2)(\alpha-c)^2}{2(n+1)^2}-\frac{\theta_O en(\alpha-c)}{n+1}$	$SW_1-\frac{n(\alpha+(s-1)\tau)(1-\tau+\tau\theta_O)e}{(n+1)(1-\delta\tau^2)}$
E	$\frac{\theta_O en(\alpha-c)}{n+1}$	$\frac{n(\alpha+(s-1)\tau)(1-\tau+\tau\theta_O)e}{(n+1)(1-\delta\tau^2)}$

Note:
$$SW_1=\frac{n(\alpha+(-1+s)\tau)\left(-(2+n+ns)\tau+2(\delta+ns\delta)\tau^3+\alpha\left(2+n-2\delta\tau^2\right)\right)}{\mathbf{2(n+1)^2(1-\delta\tau^2)}}$$

CRediT authorship contribution statement

Changmin Jiang: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Yan Liu:** Writing – review & editing, Visualization, Validation, Software, Investigation, Formal analysis.

Declaration of competing interest

None.

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Appendix A

Proof of Proposition 1:

It is easy to show that the unit cost of the airline decreases with δ, while the airline profit and the uncompensated emissions levels increase with δ. Therefore, we can obtain four cut-off values of δ, denoted by δ_1, δ_2 and δ_4, with $\delta_1 = 2(1-c)/(\alpha-2c+1)$, $\delta_2 = \left(2\alpha+c^2-2\alpha c-1\right)/(\alpha-c)^2$ and $\delta_4 = (1-c)/(\alpha-c)$. When $\delta > \delta_1$, the equilibrium unit cost of SAF is lower than c. When $\delta > \delta_2$, the equilibrium profit of the airline is larger if it purchases SAF instead of carbon offset credit. When $\delta > \delta_4$, the equilibrium emissions is larger when the airline purchases SAF instead of carbon offset credit.

However, the difference in social welfare between the two strategies does not always increase with δ:

$$SW_s–SW_o = \left\{3\left(\frac{4\theta_O e}{3}+c-\alpha\right)(-\alpha+c)\delta^2+\left(-4\alpha^2+(4\theta_O e+12c-4)\alpha-8\theta_O ec-6c^2+4\theta_O e+2\right)\delta+3\left(\frac{4\theta_O e}{3}+c-2\alpha+1\right)(c–1)\right\}\Big/8(-1+\delta)^2$$

We now want to find out when it is positive. It is easy to see that $SW_s–SW_o = 0$ has two solutions, δ_3^1 and δ_3^2.

$$\delta_3^1 = \left\{2\alpha^2+(-2\theta_O e-6c+2)\alpha+(4ce-2e)\theta_O+3c^2-\sqrt{\left(4e^2\theta_O^2-8\theta_O e\alpha+4\theta_O ec+4\alpha^2-6\alpha c+3c^2+4\theta_O e-2\alpha+1\right)(\alpha-1)^2}-1\right\}\Big/ (-\alpha+c)(4\theta_O e-3\alpha+3c)$$

$$\delta_3^2 = \left\{2\alpha^2+(-2\theta_O e-6c+2)\alpha+(4ce-2e)\theta_O+3c^2+\sqrt{\left(4e^2\theta_O^2-8\theta_O e\alpha+4\theta_O ec+4\alpha^2-6\alpha c+3c^2+4\theta_O e-2\alpha+1\right)(\alpha-1)^2}-1\right\}\Big/ (-\alpha+c)(4\theta_O e-3\alpha+3c)$$

It should be noted that, δ must be positive and less than 1 to ensure our equilibrium traffic is positive, so we can mainly analyze the function $SW_s–SW_o$ for $\delta \in (0,1)$.

For simplicity, we let $F = SW_s–SW_o$.

$$\frac{\partial F}{\partial \delta} = \frac{\left(\left(\theta_O e-\frac{\alpha}{2}+\frac{1}{2}\right)\delta-\theta_O e+\alpha-1\right)(\alpha-1)}{2(1-\delta)^3}$$

$$F|_{\delta=0} = \frac{3\left(\frac{4\theta_O e}{3}+c-2\alpha+1\right)(1-c)}{8}$$

$$\left.\frac{\partial F}{\partial \delta}\right|_{\delta=0} = \frac{(-\theta_O e+\alpha-1)(\alpha-1)}{2}$$

It is easy to find that $F|_{\delta=0} > 0 \Leftrightarrow \theta_O e > \frac{3(2\alpha-c-1)}{4}$ and $\left.\frac{\partial F}{\partial \delta}\right|_{\delta=0} > 0 \Leftrightarrow \theta_O e < \alpha - 1$. Comparing the two thresholds, we have $\frac{3(2\alpha-c-1)}{4} - \alpha + 1 = \frac{1}{4}(1-3c+2\alpha) > 0$.

Due to the denominator of F is $8(-1+\delta)^2$ and the denominator of $\frac{\partial F}{\partial \delta}$ is $2(1-\delta)^3$, when δ approaches 1 from the left, F and $\frac{\partial F}{\partial \delta}$ both approach positive infinity, i.e., $lim_{\delta\to 1^-}F = +\infty$ and $lim_{\delta\to 1^-}\frac{\partial F}{\partial \delta} = +\infty$.

Through the above analysis, we can roughly determine the image of the function F.

a) $\boldsymbol{\theta_O e < \alpha - 1, F|_{\delta=0} < 0\ \left.\frac{\partial F}{\partial \delta}\right|_{\delta=0} > 0}$, $\boldsymbol{F}$ increases with $\boldsymbol{\delta}$ and only has one zero point $\boldsymbol{\delta = \delta_3^1}$ in $(\mathbf{0},\mathbf{1})$. Fig. A1 shows the graph of the function with the corresponding parameter values that satisfy this condition.

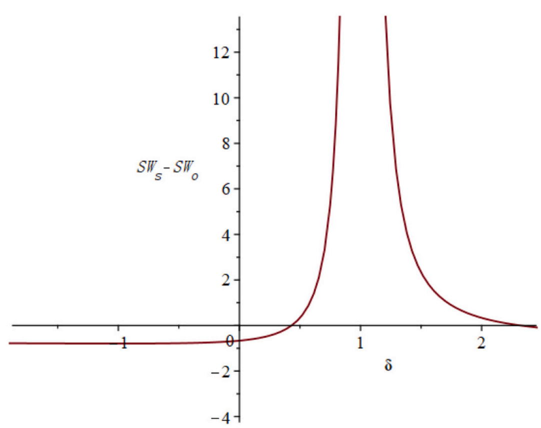

Fig. A1. The figure of $SW_s–SW_o$ when $\theta_O = \frac{1}{2}, e = 3, c = \frac{1}{3}, \alpha = 3$.

b) $\boldsymbol{\alpha - 1 < \theta_O e < \frac{3(2\alpha-c-1)}{4}, F|_{\delta=0} < 0\ \left.\frac{\partial F}{\partial \delta}\right|_{\delta=0} < 0}$, $\boldsymbol{F}$ first decreases and then increases with $\boldsymbol{\delta}$ in $(\mathbf{0},\mathbf{1})$, only has one zero point $\boldsymbol{\delta = \delta_3^1}$ in $(\mathbf{0},\mathbf{1})$. Fig. A2 shows the graph of the function with the corresponding parameter values that satisfy this condition.

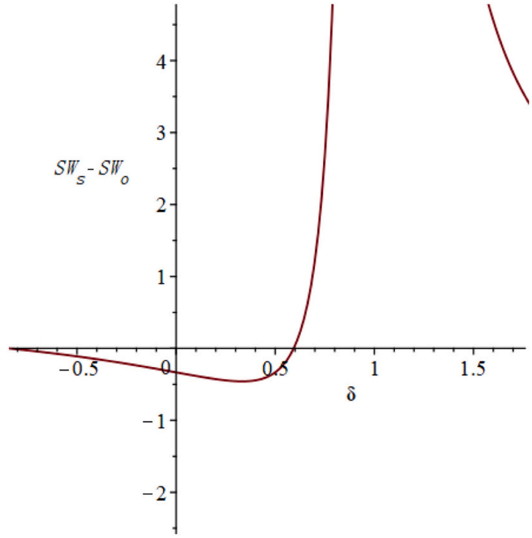

Fig. A2. The figure of SW_s–SW_o when $\theta_O = \frac{1}{2}, e = 5, c = \frac{1}{3}, \alpha = 3$

c) $\boldsymbol{\theta_O e > \frac{3(2\alpha-c-1)}{4}}$, $\boldsymbol{F|_{\delta=0} > 0}$ $\boldsymbol{\left.\frac{\partial F}{\partial \delta}\right|_{\delta=0} < 0}$, $\boldsymbol{F}$ first decreases and then increases with $\boldsymbol{\delta}$ and has two zero points $\boldsymbol{\delta = \delta_3^1}$ and $\boldsymbol{\delta = \delta_3^2}$ in $(\mathbf{0},\mathbf{1})$, and $\boldsymbol{\delta_3^1 > \delta_3^2}$. Fig. A3 shows the graph of the function with the corresponding parameter values that satisfy this condition.

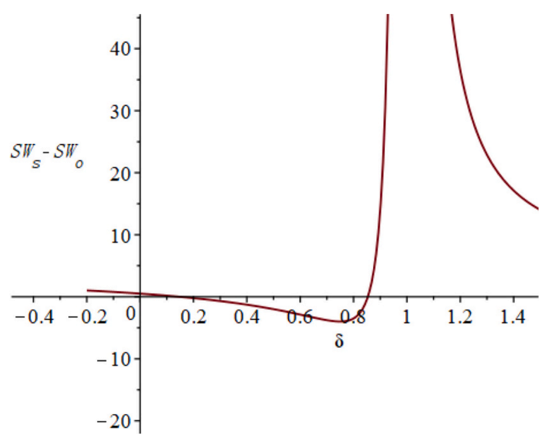

Fig. A3. The figure of SW_s–SW_o when $\theta_O = \frac{1}{2}, e = 10, c = \frac{1}{3}, \alpha = 3$

In conclusion, if $\theta_O e < \frac{3(2\alpha-c-1)}{4}$, $SW_s > SW_o$ if and only if $\delta > \delta_3^1$; if $\theta_O e > \frac{3(2\alpha-c-1)}{4}$, $SW_s > SW_o$ if and only if $\delta > \delta_3^1$ or $\delta < \delta_3^2$;

Based on those analyses, we can compare those thresholds of δ one by one. We can further show that:

$$\delta_1 - \delta_2 = -\frac{(\alpha-1)(c-1)^2}{(\alpha+1-2c)(\alpha-c)^2}$$

Since $\alpha > 1$ while $c < 1$, we should $\delta_1 - \delta_2 < 0$. As the unit cost of the airline decreases with δ, while the airline profit increases with δ, it means that in order to ensure the profit of the airline to be equal when purchasing SAF and when purchasing carbon offset credits, the unit cost of SAF will need to be lower than the unit cost of carbon credit.

For $\delta_4 - \delta_1$: $\delta_4 - \delta_1 = \frac{(c-1)(\alpha-1)}{(-2c+\alpha+1)(\alpha-c)}$

Since $\alpha > 1$ while $c < 1$, we should $\delta_4 - \delta_1 < 0$. So, we have $\delta_4 < \delta_1 < \delta_2$.

Through simple calculations using Mathematica, we can easily find that $\delta_3^2 < \delta_4 < \delta_3^1$ always holds.

Since the size of δ_3^2 is not greatly related to the main object we want to analyze, we will ignore it in the subsequent comparisons. The reason for the appearance of δ_3^2 as a positive threshold is that when the uncompensated emission rate is relatively large and the SAF production economics of scale is still relatively small, the SAF cost is too high, $Q_s > Q_o$, which leads to $E_s > E_o$, so overall $SW_s > SW_o$. But as δ increases, E_s starts to increase, which will then lead to $SW_s < SW_o$. However, this is only an extremely special and particular case, and through simple analysis, we find that the size relationship between δ_3^2 and other thresholds is constant, so in the subsequent discussions, we will mainly focus on the size relationship between δ_3^2 and other thresholds.

By simple calculation, we conclude that

a) When $\mathbf{0} < \boldsymbol{\theta_O} < \frac{-1-c+2\alpha}{4e}$, $\boldsymbol{\delta_3^1} < \boldsymbol{\delta_1}$, so $\boldsymbol{\delta_4} < \boldsymbol{\delta_3^1} < \boldsymbol{\delta_1} < \boldsymbol{\delta_2}$;

b) When $\frac{-1-c+2\alpha}{4e} < \boldsymbol{\theta_O} < \frac{c+c^2-\alpha-3c\alpha+2\alpha^2}{-4e+4e\alpha}$, $\boldsymbol{\delta_1} < \boldsymbol{\delta_3^1} < \boldsymbol{\delta_2}$, so $\boldsymbol{\delta_4} < \boldsymbol{\delta_1} < \boldsymbol{\delta_3^1} < \boldsymbol{\delta_2}$;

c) When $\boldsymbol{\theta_O} > \frac{c+c^2-\alpha-3c\alpha+2\alpha^2}{-4e+4e\alpha}$, $\boldsymbol{\delta_1} < \boldsymbol{\delta_3^1} < \boldsymbol{\delta_2}$, so $\boldsymbol{\delta_4} < \boldsymbol{\delta_1} < \boldsymbol{\delta_2} < \boldsymbol{\delta_3^1}$.

For social welfare, we should take the uncompensated emission into consideration. If the uncompensated emission rate is large, it could be more difficult for SAF production scale to enhance social welfare when airlines purchase SAF. Thus as θ_O increases, it becomes harder for δ to improve SW_s.

Q.E.D

Proof of Proposition 2:

In the proof of Proposition 1, we have already shown that if $\theta_O > \frac{c+c^2-\alpha-3c\alpha+2\alpha^2}{-4e+4e\alpha}$, $\delta_2 - \delta_3^1 < 0$ holds. Since the airline profit and the social welfare both increase with δ, this conclusion is equivalent to that the unit cost of SAF is lower to ensure social welfare to higher when purchasing SAF than when purchasing carbon offset credits, compared with the case of airline profit.

Q.E.D

Proof of Proposition 3:

Similar as the proof of Proposition 1, it is still true that the unit cost of the airline decreases with δ, while the airline profit and the social welfare both increase with δ. In other words, we can still obtain the four cut-off values of δ, which we denote as $\widetilde{\delta_1}$, $\widetilde{\delta_2}$, $\widetilde{\delta_3}$ and $\widetilde{\delta_4}$. We further show that $\widetilde{\delta_1} = (n+1)(1-c)/[n\alpha-(n+1)c+1]$, $\widetilde{\delta_2} = \left(2\alpha+c^2-2\alpha c-1\right)/(\alpha-c)^2$,

$$\widetilde{\delta_3} = \left\{2\left(c-\tfrac{\alpha}{2}-\tfrac{1}{2}\right)(n+1)e\theta_O+(-\alpha+c)^2n+\alpha^2+(-4c+2)\alpha+2c^2+\sqrt{(\alpha-1)^2\left((\theta_Oe-\alpha+c)^2n^2+\left(2e^2\theta_O^2+2e(c-2\alpha+1)\theta_O+2(-\alpha+c)^2\right)n+(\theta_Oe-\alpha+1)^2\right)}-1\right\}/(2e(n+1)\theta_O+(n+2)(-\alpha+c))(-\alpha+c)$$

and $\widetilde{\delta_4} = (1-c)/(\alpha-c)$.

We can see that $\widetilde{\delta_2}$ and $\widetilde{\delta_4}$ does not change together with n, but $\widetilde{\delta_1}$ and $\widetilde{\delta_3}$ do. In particular,

$$\frac{\partial\widetilde{\delta_1}}{\partial n} = -\frac{(\alpha-1)(1-c)}{[n\alpha-(n+1)c+1]^2} < 0$$

$$\begin{aligned}\frac{\partial\widetilde{\delta_3}}{\partial n} = & \Big\{-\Big(\Big((-1+\alpha)\Big((-1+\alpha)\left((c-\alpha)\left(-1+c^2(2+n)+2\alpha-2c(2+n)\alpha+(1+n)\alpha^2\right)+e\left(-2+c^2(4+3n)+(4+n)\alpha+2(1+n)\alpha^2\right.\right.\\ & \left.\left.-c(n+8\alpha+5n\alpha)\right)\theta_O+e^2(1+n)(-2+3c-\alpha)\theta_O^2\right)+(-(c-\alpha)(-1+\alpha)\\ & -e(-2+c+\alpha)\theta_O)\sqrt{(-1+\alpha)^2\left((1-\alpha+e\theta_O)^2+n^2(c-\alpha+e\theta_O)^2+2n\left((c-\alpha)^2+e(1+c-2\alpha)\theta_O+e^2\theta_O^2\right)\right)}\Big)\Big)\Big\}\Big/\\ & \left((c-\alpha)((2+n)(c-\alpha)+2e(1+n)\theta_O)^2\sqrt{(-1+\alpha)^2\left((1-\alpha+e\theta_O)^2+n^2(c-\alpha+e\theta_O)^2+2n\left((c-\alpha)^2+e(1+c-2\alpha)\theta_O+e^2\theta_O^2\right)\right)}\right) < 0\end{aligned}$$

Q.E.D

Proof of Proposition 4:

It is easy to show that

$$\frac{\partial\pi_i}{\partial\tau} = \frac{2(\alpha-\tau)(\alpha\delta\tau-1)}{(n+1)^2(1-\delta\tau^2)^2}$$

which will be positive when $\alpha\delta\tau-1>0$ and negative otherwise. This condition can be rewritten as $\alpha\delta > 1/\tau$. Since $1/\tau$ is the SAF multiplier, we can conclude that as long as the SAF multiplier is smaller than $\alpha\delta$, the decrease of τ (meaning the increase of the SAF multiplier) will decrease π_i, essentially reducing the profits of the airlines.

We also have

$$\frac{\partial E_i}{\partial\tau} = \frac{(\delta(\alpha\theta_O-\alpha-1)\tau^2+(2+2\alpha\delta-2\theta_O)\tau-1-\alpha+\alpha\theta_O)en}{(n+1)(\delta\tau^2-1)^2}.$$

Let $R_\delta = \frac{1+\alpha-2\tau-(\alpha-2\tau)\theta_O}{\tau(2\alpha-\tau-\alpha\tau+\alpha\tau\theta_O)}$, when $0<\delta<R_\delta$, $\frac{\partial E_i}{\partial\tau}<0$;when $R_\delta \le \delta < \frac{1}{\tau^2}$, $\frac{\partial E_i}{\partial\tau} \ge 0$. It should be noted that $\delta < \frac{1}{\tau^2}$ is required to ensure the equilibrium passenger number be positive. Comparing R_δ with $\frac{1}{\alpha\tau}$, which is the threshold to let $\frac{\partial\pi_i}{\partial\tau}$ positive, we find that if $\theta_O < \frac{\alpha-1}{\alpha}$, $R_\delta > \frac{1}{\alpha\tau}$, else if $\theta_O \ge \frac{\alpha-1}{\alpha}$, $R_\delta \le \frac{1}{\alpha\tau}$.

Q.E.D

Proof of Proposition 5:

$$\begin{aligned}\left.\frac{\partial SW}{\partial\tau}\right|_{\tau=1} = & -n\left(\left((n+1)(-1+(\theta_O+1)\alpha)e-2\alpha^2+2\alpha\right)\delta^2+\left(-2(\alpha+\theta_O-1)(n+1)e+(2n+2)\alpha^2-3\alpha n+n-2\right)\delta-(n+1)((\theta_O-1)\alpha-2\theta_O+1)e\right.\\ & \left.-(\alpha-1)(n+2)\right)\Big/(n+1)^2(\delta-1)^3\end{aligned}$$

$$\left.\frac{\partial\pi_i}{\partial\tau}\right|_{\tau=1} = \frac{2(\alpha-1)(\alpha\delta-1)}{(\delta-1)^2(n+1)^2}$$

$$\left.\frac{\partial \pi_i}{\partial \tau}\right|_{\tau=1} - \left.\frac{\partial SW}{\partial \tau}\right|_{\tau=1} = \Big(e(-1+(\theta_O+1)\alpha)\delta^2 + \big(2\alpha^2+(-2e-3)\alpha+1+(-2\theta_O+2)e\big)\delta + (-1+(-\theta_O+1)e)\alpha+1+(2\theta_O-1)e\Big)n^2$$
$$+(\delta-1)\big((-2\alpha^2+(2+(\theta_O+1)e)\alpha-e\big)\delta+(2+(\theta_O-1)e)\alpha-2+(-2\theta_O+1)e\big)n+2(\alpha-1)(\alpha\delta-1)(\delta-1)\Big/(n+1)^2(\delta-1)^3$$

Under the circumstances that $\partial\pi_i/\partial\tau > 0$, that is $\alpha\delta\tau - 1 > 0$ and $\alpha\delta - 1 > 0$ when $\tau = 1$,

If $0 < e < R_e$ or both $e > R_e$ and $0 < \theta_O < R_{\theta_O}$ are met, $\left.\frac{\partial \pi_i}{\partial \tau}\right|_{\tau=1} < \left.\frac{\partial SW}{\partial \tau}\right|_{\tau=1}$, which means it is harder for a SAF multiplier to improve social welfare than improving airline profit when the multiplier is small.

Otherwise, if $e > R_e$ and $R_{\theta_O} < \theta_O < 1$, $\left.\frac{\partial \pi_i}{\partial \tau}\right|_{\tau=1} > \left.\frac{\partial SW}{\partial \tau}\right|_{\tau=1}$, which means it is harder for a SAF multiplier to improve airline profit than improving social welfare when the multiplier is small.

The expressions for the two thresholds are

$$R_e = \frac{(-1+\alpha)(2(-1+\delta)(-1+\alpha\delta) - 2n(-1+\delta)(-1+\alpha\delta) + n^2(-1+(-1+2\alpha)\delta))}{n(1+n)(1-\delta)(-1+(-1+2\alpha)\delta)}$$

$$R_{\theta_O} = \left\{(-1+\alpha)\big(2(-1+\delta)(-1+\alpha\delta) - 2n(-1+\delta)(-1+\alpha\delta) + n^2(-1+(-1+2\alpha)\delta)\big)\right\}/n(1+n)(1-\delta)(-1+(-1+2\alpha)\delta)$$

Q.E.D

Proof of Proposition 6:

It is easy to show that

$$\frac{\partial \pi_i}{\partial \tau} = \frac{2(\alpha+(s-1)\tau)(\alpha\delta\tau+s-1)}{(n+1)^2(1-\delta\tau^2)^2}$$

which will be positive when $\alpha\delta\tau + s - 1 > 0$ and negative otherwise. This condition can be rewritten as $\alpha\delta > (1-s)/\tau$ or $s > 1 - \alpha\delta\tau$.

(To ensure the airline's cost are positive, we need to let $s < 1 - \frac{\alpha\delta n\tau}{-\delta\tau^2+n+1}$.)

Q.E.D

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