Proceedings of the 4th International
Aviation Management Conference,
IAMC – 2022 Dubai, UAE
November 21-22, 2022

The Introduction of Sustainable Aviation Fuels Challenges and Options

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Abstract The aviation industry is challenged to reduce its climate impact. The most promising strategy, at least in the short- to medium term, will be the introduction of sustainable aviation fuels (SAF). These fuels feature substantially reduced carbon life-cycle emissions in comparison to fossil fuels. In Europe, a mandatory quota for the use of sustainable fuels will most likely be introduced, starting in the year 2025. The introduction of a blending mandate by governments and the European Commission is associated with a range of challenges. The purpose of this paper is to discuss the economics of climate change mitigation in aviation and the role SAFs can play. The economic issues associated with the introduction of SAFs are analyzed, with a particular focus on the European Commission's proposal for a blending mandate. Several suggestions for improvement are discussed. Despite its relatively high costs, a key finding of the discussion is that SAFs will play an important role in the decarbonization of aviation.

***Key Words** Sustainable Aviation Fuels, Climate Change, Aviation Regulation.*

1. Introduction

The global community is challenged to limit the impacts of climate change to a tolerable level. With the Paris Agreement concluded in 2015, it is the legally binding aim to limit the average global temperature increase "to below 2°C above pre-industrial levels" (United Nations, 2015). Promising strategies have been developed in various sectors of the economy to reduce CO_2 emissions., e.g. by scaling up renewable energies or the direct use of electricity in ground transport. These strategies are considered to achieve CO_2 emissions reductions at relatively low costs (Gillingham & Stock, 2018). The aviation industry is particularly challenged, as it is a hard-to-abate sector, where the replacement of the energy carrier by a low carbon alternative is particularly difficult. Jet fuel, as a mixture of different hydrocarbons, features optimal characteristics in terms of performance, energy density and operability (U.S. Department of Energy, 2020). However, it releases CO_2, which was removed from the biosphere millions of years ago and safely stored underground. Other energy carriers either feature an energy density which is too low (e.g. batteries, extensively analyzed in Viswanathan *et al.*, 2022) or, like hydrogen, would require a complete change of the aviation system, including fuel and airport infrastructure as well as the expensive and time-consuming development and certification of new aircraft technology (Noland, 2021). Hence, the introduction of sustainable drop-in hydrocarbon aviation fuels (SAF) from non-fossil origins is considered by many stakeholders as a viable strategy to decarbonize aviation in the short to medium term.

This paper discusses the economic challenges of introducing SAF, such as the economic efficiency of this decarbonization strategy, societal and political implications and the potential impacts of regulatory instruments designed to promote the market uptake of these fuels. The discussion is carried out against the background of the European policy objective of a mandatory blending quota to be introduced by 2025 (European Commission, 2021).

The structure of the paper is as follows: to set the scene, the theory and practice of the reduction of carbon emissions in the aviation sector is discussed, which has led to the regulatory pressure for the introduction of sustainable aviation fuels in Europe. Subsequently, the plans of the European

Commission for a blending mandate are briefly outlined. This is followed by an analysis of the economic and competitive impacts of a blending mandate and a discussion of the potential alternatives. The paper concludes with a summary of the main findings.

2. Reducing Carbon Emissions in Aviation in Theory and Practice

Climate change, which is primarily caused by CO_2 emissions, is a classic example of a negative externality that has been known to economists at least since the work of Pigou (1920). Negative externalities lead to market failure, if they are not considered in the price setting process. One approach to re-instate economic efficiency is to place a uniform price on CO_2 emissions, aligning the private and social costs of emissions. Pigou suggested to install an environmental tax that would cover for the externalities. Another approach is assigning property rights to the atmosphere as "dump" for carbon emissions, following the property rights theory of Coase (2013). The right to release carbon dioxide emissions is then securitized in tradable units, also called permits or allowances. Under economically optimal conditions, the total number of allowances in such a cap-and-trade scheme is limited to a quantity where marginal damage costs equal marginal abatement costs and a socially efficient level of emissions is achieved (Verbruggen, 2021). Emissions will then be priced and a price signal is sent to emitters, which have the choice either to reduce emissions (if this is cheaper than the price of an allowance) or to continue emitting (if abatement costs are higher than the value of allowances). The two approaches (taxes vs. cap-and-trade) feature similarities and differences, which are widely discussed in the economic literature (e.g. Weitzman, 1974; Stavins, 2020).

As straightforward as it looks on paper, implementation of such a first-best solution to reinstate economic efficiency, in reality, is rather difficult. Even within most jurisdictions, carbon emissions are non-uniformly priced - for instance, in Germany, a mix of taxes, carbon prices and emissions trading exist. For instance, aviation is part of the EU-ETS, where CO_2 prices have exceeded 90 €/CO_2 during the year 2022 (European Energy Exchange, 2022), while in the newly introduced national emission trading scheme for fossil fuels used in heating and ground transport is priced at initially 25 €/CO_2 (Federal Government of Germany, 2020). This leads to unequal pricing for each ton of carbon, depending on which sector CO_2 is emitted. In the aviation domain, the international dimension complicates a practical implementation of a uniform carbon price even more. While in Europe, carbon emissions of flights within the European Economic Area are strictly regulated in a cap-and-trade scheme, the majority of emissions in aviation remain effectively unregulated. Doubts are raised as to whether CORSIA, the global carbon offsetting and reduction scheme for international aviation, meets the criteria of economic efficiency in climate protection towards achievement of the objectives outlined in the Paris Agreement (Murphy, 2019; Wozny *et al.*, 2022; Schneider & Wissner, 2022). The scheme does neither strive to reduce emissions below the baseline of the year 2019/2020 nor do the offsets effectively contribute to the removal of CO_2 from the atmosphere. The complexity of assessing the quality of offsets is, for instance, explained by Broekhoff and Spalding-Fecher (2021).

As the existing instruments can be considered as insufficient to effectively reduce the climate impact of aviation, pressure from the European society and politics on the aviation sector has intensified in recent years. This development has become a manifest business risk for the growth of the aviation industry, as sustainable means of travel and the reduction of air trips for business and private purposes have become widespread topics in society.

One topic in the focus of public attention is the potential of SAF to reduce the climate impact of aviation. Depending on the production pathway, the CO_2 reduction potential per unit of fuel can be more than 58 % (Pavlenko & Searle, 2021) compared to a conventional fuel baseline. Some production pathways, under consideration of full lifecycle emissions and indirect impacts, can even feature overall negative emissions. Given the high potential for emissions reductions, legislators on national and European level have started drafting regulations prescribing the use of SAF in future by mandatory quota regulations (European Commission, 2021). Mandatory quotas belong to the group of command-and-control instruments, as opposed to market-based instruments like a cap-and-trade scheme.

The introduction of SAF is, however, not undisputed. From the perspective of economic efficiency, carbon reduction by sustainable aviation fuels is likely to be a relatively expensive strategy, reducing welfare in comparison to a carbon tax (Jiang & Yang, 2021). The economic evaluation of SAF largely depends on its relative costs compared to conventional fuels. Currently, it is estimated that SAF can be two to six times more expensive than conventional jet fuel, depending on the production pathway. This results in abatement costs per ton of CO_2 of 200 € to 500 € for SAF from biogenic feedstocks and potentially even higher costs for power-to-liquid fuels (Pavlenko *et al.*, 2019). Butterworth (2021) finds that in the European Union, two-thirds of CO_2 emissions could be reduced at a cost of less than 200 €/t. In a merit order, wind and solar power, as well as efficiency gains in industry and home heating, feature particularly high reduction potentials, mostly at abatement costs even below 100 €/t.

Hence, it can be argued that a single carbon price would be the first best solution, so that emitters of CO_2 could decide in which sectors carbon emission reductions could be realized at the lowest cost and by which technologies. However, this line of argumentation, being critical of the introduction of SAF, neglects the following points:

First, the learning curve and scale effects are likely to reduce the costs of SAF. Several optimistic studies suggest that in the long run, SAF costs will only be marginally higher than conventional fuels. Wille *et al.* (2022) argue that with a reduction in costs for renewable electricity and in combination with carbon prices for conventional fuel, the cost increase per ticket could be as low as 16 %. Second, the current geopolitical debate shows that a higher degree of energy independence is an important political goal. SAF has the potential to reduce, at least partially, the dependency on potentially politically unstable suppliers of fossil fuels. Third, the societal pressure requires the aviation industry to realize in-sector emissions reductions. A defensive position by the industry, arguing that abatement costs are too high, is unlikely to be accepted by large segments of society and would jeopardize the future development and growth prospects of aviation through a loss of social acceptance. Fourth, due to the international context of aviation, a carbon pricing mechanism putting a uniform price on all CO_2 emitted in aviation globally is unlikely to develop. Fifth, using SAF could significantly reduce the non-CO_2 effects of aviation, which mainly emerge due to soot particles, oxidized sulphur species, NO_x and water vapor emissions (European Commission, 2020). The composition of SAF can be optimized to be low on aromatics and basically free of sulphur particles. This could reduce contrail and cirrus cloud formation. Moreover, local air quality could improve by reducing fine particle emissions and their secondary formation. Hence, the benefits of SAF due not only have to be quantified with regard to CO_2 reduction but also with regards to the reduction of non-CO_2 and local air quality effects. It is currently estimated that non-CO_2 effects currently contribute more than half of the total climate effect of aviation (European Commission, 2020). Sixth, alternative strategies, such as the introduction of more energy efficient aircraft, will be insufficient to effectively reduce CO_2 emissions of aviation in absolute terms. In the past, a decoupling of aviation emissions and traffic could be observed, reducing specific emissions per passenger kilometer. But as traffic growth has exceeded the rate of efficiency improvements, absolute emissions have been growing (Schaefer, 2012). For the next 20 years, Boeing and Airbus expect a traffic growth of 3.8% and 3.6%, respectively (Airbus, 2022; Boeing, 2022). Efficiency improvements, which include both aircraft/engine technology and operational procedures, are in the order of 1.2% (Schaefer, 2012). Hence, absolute CO_2 emissions growth of aviation will be in the order of 2.4-2.6%, which contradicts the objective of keeping global warming to 1.5°C above pre-industrial levels (United Nations, 2015).

To sum it up, the realization of an optimal solution to counter climate change in aviation, according to economic textbooks, will be very unlikely to be realized. When considering a wider set of objectives than CO_2 reduction, the introduction of sustainable aviation fuels can be considered a feasible second-best solution to tackle a wider set of above-mentioned issues.

3. The European Commission's Proposal for a SAF Blending Mandate

3.1. Outline

In July 2021, the European Commission published its proposal ReFuelEU Aviation (European Commission, 2021) for the introduction of a SAF blending mandate as part of the "Fit for 55 package" under the European Green Deal. With this step, the introduction of SAF in Europe is about to be harmonized, as various European governments had previously introduced mandatory SAF quotas on a national level.

The European Commission's proposal stipulates that a growing share of SAF, from initially 2 % in the year 2025 up to 63 % in the year 2050, must be used by all aircraft operators taking off from any airport within the European Economic Area with more than one million passengers or 100,000 tons of freight. Figure 1 provides information on the trajectory of the blending quota over time, which includes a sub-quota for power-to-liquid fuels (also known as e-fuels due to the high intensity of electricity in the production process). This sub-quota is intended to support the technology that, based on current knowledge, has higher production costs than other SAF production pathways. The proposal includes reporting requirements on the fuel required and the fuel uplifted as well as a ban on tinkering. These provisions are intended to reduce potential disadvantages for European airlines in relation to their competitors operating a predominant share of their flights from airports falling outside the scope of the proposed regulation.

The proposal does not include provisions aimed at bridging the cost differential between fossil fuels and SAF, a major concern of airlines who fear that the cost differential will severely impact their competitiveness. The ambitious blending quota also poses technological challenges to the upscaling of SAF production. We estimate that in 2035 approximately 13 million tons of SAF will be required to fulfil the European quota. This figure is expected to increase to over 47 million tons of SAF in 2050 (Figure 2). SAFs from biogenic sources are likely insufficient to cover more than a quarter of this demand (O'Malley *et al.*, 2021). The bulk of the remainder must be covered by power-to-liquid fuels in excess of the mandatory sub-quota. This, in turn, will require a massive scale-up of renewable electricity generation. It is estimated that 42 kWh of electricity is required to produce one kilogram of power-to-liquid fuel (Drünert *et al.*, 2020), which contains, in the end, only 12 kWh of useable energy. This shows the relatively low efficiency of the overall process, which is a strong argument against the widespread deployment of e-fuels until electricity from renewable sources is abundant.

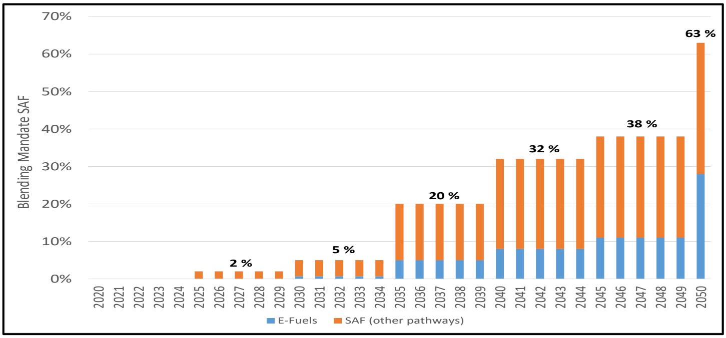

Figure 1: Trajectory of the SAF blending quota as proposed by the European Commission. Source: Own figure based on data of European Commission (2021).

Based on the estimation that 35 million tons of SAF from the power-to-liquid pathway are required in the year 2050, 1,470 TWh of renewable energy would be required as input. This equals half of the total electricity generation and 50% more than the electricity generation from renewable sources in the European Union in 2020 (EUROSTAT, 2022). These figures illustrate the challenge the industry is facing if the targeted SAF quotas are to be met.

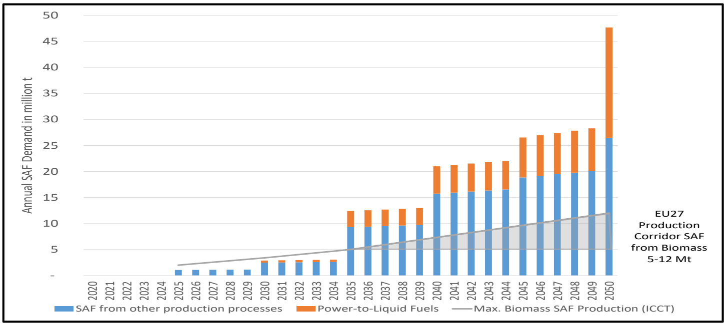

Figure 2: Expected quantities of SAF to fulfil the blending quota as proposed by the European Commission (Grimme, 2022).

3.2. Economic and Competitive Impacts

A mandate to use sustainable aviation fuels at rising quantities over time is likely to increase costs for airlines and, in case a shift on end-users is possible, ultimately for passengers and the shippers of air cargo. With a relatively high share of SAF likely to come from the power-to-liquid production pathway, enormous investments in renewable electricity generation will be required, in addition to the investments for the components of fuel production, such as electrolyzers, syngas processing, syncrude refining and potentially also direct CO_2 air capture.

From a competitive point of view, European airlines fear a disadvantage predominantly in long-haul travel. Non-stop flights, e.g. from Europe to East Asia will be subject to the blending mandate for the full flight distance, affecting the European network airlines with direct services as well as the airlines from third-countries in the region, such as Korean Air, JAL, ANA, Singapore Airlines, Thai Airways and others. As an example, for an origin-destination itinerary from Frankfurt to

Singapore (Figure 3), the full flight distance of a non-stop flight offered by Lufthansa or Singapore Airlines would be subject to the blending mandate, as the flight originates in the European Union. In comparison, only 20% of the flight distance would be subject to the EU blending mandate for an itinerary Frankfurt-Istanbul-Singapore, as the longer flight segment from Istanbul to Singapore does not fall under the EU legislation.

However, it should be noted that IATA, as the main industry organization, has committed to up to 65% SAF deployment by 2050 as part of its 'Net Zero Strategy' published at the 2021 AGM (IATA, 2021). Hence, if airlines took this voluntary commitment seriously, competitive distortions would be minimal. All major network airlines competing in long-haul markets globally are members of IATA and should be subject to voluntary commitment.

Figure 3: Exemplary itinerary Frankfurt-Singapore / non-stop and with a transfer in Istanbul. Source: ww.gcmap.com.

In addition to the issue of long-haul itineraries and the competition with hubs and airlines outside the scope of the EU blending mandate, intra-EU holiday traffic (and destinations) could be affected by traffic flows to be shifted to non-EU locations. For instance, holiday traffic to Spain, Italy and Greece could be diverted to Tunisia or Turkey, where only the outbound segment is subject to the EU blending mandate, but not the return segment. This form of carbon leakage would undermine the effectiveness of the blending mandate. However, conclusive evidence of carbon leakage due to the EU ETS as a similar policy adding costs only to certain route groups is still lacking.

4. Alternative Approaches / Flanking Measures

4.1. Book-and-claim approach

A major issue with the proposal of the European Commission is that the SAF quota must be met at each European airport exceeding one million passengers or 100,000 tons of cargo. The uniform application of the blending mandate puts logistical challenges in the foreground, as SAF must be offered at the quota prescribed by the EU Regulation at each individual airport. This leads to potentially long transport distances from the SAF refineries, which is also associated with additional energy consumption and emissions. Alternatively, it is more efficient to concentrate SAF usage at airports close to the respective refineries. Under such a book-and-claim approach, airlines operating from airports with favorable access to SAF would exceed the quota, while airlines operating from airports with less favorable access would fall below the quota. Compensation could be achieved ex post via tradable certificates so that airlines that used a higher proportion of the more expensive fuel would be compensated. Such a scheme could also incentivize network airlines to invest in building larger SAF facilities at their hub, which could fulfil a large part of their network-wide SAF obligations. Such an approach is likely to be more efficient than the initial proposal of the European

Commission, as it would reduce logistics costs and SAF transport emissions and incentivize larger SAF installations at key hubs.

4.2. Use of Aviation-specific State Revenues for Subsidizing SAF Introduction

A key objective of the blending mandate is to create a market for SAF, which would otherwise not develop because of the cost differentials compared to fossil fuels. Private investment in SAF production is incentivized as there is no alternative for airlines to purchase increasing quantities of SAF to meet the use obligation. In this regard, it is not a necessary consequence to take additional flanking measures to support SAF market development. However, the aviation industry fears competitive distortions with a mandate prescribing the use of more expensive fuel. In order to reduce the cost impacts, various industry suggestions are discussed, which have in common to use of public funds to reduce the cost differential between SAF and fossil fuels. A key objective of the aviation industry is earmarking of revenues from the aviation sector for the introduction of SAF. While in the existing regulations, limited earmarking is envisaged, e.g. for the revenues generated by the sale of allowances in the EU ETS, it does by definition not exist for tax revenues. There is no logical consequence that any taxes collected from aviation activities, such as air passenger duties, must be reallocated to the aviation sector. In case it is the political objective to reduce the costs of the introduction of SAF for the aviation industry, various instruments could be applied.

Contracts for differences are an efficient tool to create incentives for investments in technologies that are not yet competitive in terms of production costs. In such a contract, one party (typically a government branch) guarantees to take over the differential between production costs and market prices of SAF. The instrument is very well suited to overcome the initial obstacle for investments in SAF technology. The historical experience with renewable energy projects like wind and photovoltaic power generation has shown that production facilities constructed at an early stage will not be competitive in the medium to longer term. Between 2010 and 2020 the cost of photovoltaic installations has fallen by 81%, that of wind power by more than 30% (International Renewable Energy Agency, 2021). Nevertheless, such facilities must be built in order to achieve long-term learning curve effects. The advantage of contracts for difference is also the openness concerning technologies to be applied, as a tendering process could only prescribe a certain quantity of low-carbon SAF as an objective, while tenderers can decide on their own which production pathway is the most promising. In the end, the production pathways with the smallest difference between market price and production costs are determined in an order-of-merit approach.

Generally, it is likely that the price differential of the full quantity of SAF to be used in Europe cannot be covered by contracts for difference – if we assume a quantity of about 10 million tons annually in the year 2035 as shown in Figure 2, and an average price difference between SAF and fossil fuel of 1,500 € per ton, public subsidies would amount to around 15 billion € annually. It is doubtful whether European governments would be willing to support the aviation sector by this scale. The majority of costs are likely to be ultimately borne by passengers and shippers of air cargo.

Another conceivable instrument would be a fossil fuel surcharge, which would be redistributed to subsidize SAF price differentials. Such an instrument could be constructed in analogy to the feed-in tariff in the German electricity sector, which was in force from 2000 to 2022. With this instrument, electricity consumers pay a surcharge that encourages investment in renewable energy production. With the help of the renewable energy surcharge, the share of electricity generated from renewable sources in Germany has grown over time to over 45 % in 2020 (Umweltbundesamt, 2021). A positive aspect of the surcharge is that the cost burden is theoretically evenly distributed over all users, while also competitive elements could be integrated, such as competitive tendering for subsidies to bring the most efficient SAF production pathways into the market. A central challenge in defining such a surcharge is the right incentives for SAF producers: If the incentive payment is too low, it would be unattractive to build up production capacities. If the level is too high, windfall profits will be generated, the cost burden on users will be excessive, and incentives to become more efficient in the production of SAF will be too small. The level of such a surcharge will be dependent to a large extent on the price differential between SAF and fossil fuel and the intended SAF quota. Assuming a price differential of 1,500 € per ton in 2035 and 1,000 € per ton in 2050, the quotas outlined in Figure 1 and SAF demand as shown in Figure 2, the surcharge would amount to 375 € per ton of fossil fuel in 2035 and 1,700 € per ton of fossil fuel in 2050. In 2050, almost 50 billion € would have to be re-distributed. In order to relieve users, the surcharge could be subsidized by the state if revenues from taxes or the auctioning of CO_2 allowances were made available for the introduction of the SAF. But overall, these results make it clear that the financial burden will be significant, regardless of who ends up bearing the costs.

Additional flanking measures that could be introduced are also subsidies on investments for research and development or loan guarantees for SAF production facilities in order to reduce the CAPEX cost share. In the USA, tax credits have been successfully applied in order to increase the use of biofuels in ground transport. In August 2022, the United States Senate approved a blender's tax credit of between 1.25 US-$ to 1.75 US-$ per gallon of SAF in order to support the market uptake of SAF (United States Congress, 2022). It is intended that this instrument will support the "Sustainable Aviation Fuel Grand Challenge", with milestones of 3 billion gallons in 2030 and 35 billion gallons in 2050.

5. Conclusion

In this paper, we discussed the economic challenges associated with the introduction of sustainable aviation fuels in light of the proposal of the European Commission for a blending mandate to be applicable at all major airports in the European Union. Although the cost of sustainable aviation fuels makes this approach to CO_2 reduction not economically efficient in the short term, there are a number of arguments in favor of this strategy. The key issue the aviation industry is facing is pressure from society and politics to reduce CO_2 emissions in the aviation sector itself. For the introduction of SAF, different regulatory instruments can be applied. In the EU, a blending mandate is stipulated, which will ultimately impose costs on aviation users (passengers and shippers of cargo), if no flanking measures of support will be added. The aviation industry pushes for earmarking of government revenues to be channeled into SAF production so that the costs for users will be reduced. The overall costs of the transition to SAF for the aviation sector depend to a large extent on the cost differential between SAF and fossil fuel and the quota prescribed in the blending mandate. For the EU, we expect demand for SAF in the order of 47 million tons in the year 2050. But no matter which stakeholder, in the end, has to bear the costs, the transition to SAF will be expensive, especially in the initial phase, when learning curve effects and economies of scale are not yet realized.

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