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APPLICABILITY OF THE SAF OPERATION – CASE STUDY OF A CZECH REGISTERED BUSINESS AIRCRAFT OPERATOR ON FLIGHTS WITHIN EUROPE

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Abstract. The aim of this paper is to develop a fundamental model for assessing the potential of Sustainable Aviation Fuel (SAF) utilization in business aviation. It investigates the feasibility and strategic integration of SAF within Czech registered business aircraft operator on flights within Europe, with a focus on its environmental and economic implications. The study evaluates the carriers' networks by establishing two refueling strategies and identifying key factors for calculating emissions and costs. Specifically, the Minimum Refueling Strategy and Maximum SAF Refueling Strategy are analyzed. Through a thorough analysis, this research aims to offer actionable insights for aviation companies, highlighting the dual benefits of SAF in promoting both sustainability and cost efficiency. Current EU ETS regulations exempt operators emitting less than 10 000 tonnes of CO_2 annually, a threshold many operators aim to stay below. However, as the EU intensifies its climate targets, smaller operators must anticipate greater regulatory and financial pressures related to emissions. This represents a pivotal move toward a more inclusive and stringent emissions trading system, aligned with sustainability goals. SAF adoption emerges as a promising solution for business aviation, as its use would significantly reduce CO_2 emissions and associated costs for operators. By offering a comprehensive overview and strategic recommendations, this study aims to contribute to the ongoing discussion on sustainable aviation practices and assist stakeholders in making informed decisions regarding the adoption of SAF.

Keywords: Sustainable Aviation Fuel (SAF), business aviation, environmental impact, carbon emissions, refueling strategies, economic analysis, Czech registered business aircraft operator.

1. Introduction

The aviation industry, integral to global economic and social connectivity, is simultaneously an important contributor to environmental degradation, primarily due to its substantial carbon dioxide and other greenhouse gases emissions. As global awareness of climate change's impacts intensifies, there is a compelling need for the aviation sector to reduce its environmental footprint. This urgency is underscored by the growing scrutiny from governments, regulatory bodies, and the public demanding sustainable practices.

Sustainable Aviation Fuel (SAF) represents a transformative approach to mitigate aviation's environmental impacts by providing an eco-friendly alternative to conventional jet fuels. According to the U.S. Department of Energy [1], SAF refers to a category of biofuels derived from renewable feedstocks, offering an alternative to conventional fossil-based jet fuels such as Jet A-1. These feedstocks include waste oils and fats (such as used cooking oil), agricultural residues, lignocellulosic biomass, and even algae. SAF is considered a "drop-in" fuel, meaning it can be blended with conventional jet fuel and used in existing aircraft engines and infrastructure without the need for significant modifications. This research paper delves into the application of SAF within the Czech business aviation landscape, examining its environmental benefits against economic implications and exploring strategic integration pathways.

The role of aviation in global carbon emissions is significant, with the industry accounting for approximately 2 % of global CO_2 emissions. This figure is projected to rise dramatically if reliance on traditional fossil fuels persists [2]. The International Air Transport Association (IATA) has recognized the critical nature of this challenge, setting forth an ambitious agenda to reduce aviation's emissions to 50 % of 2005 levels by the year 2050, which underscores the pivotal role of SAF in achieving these goals [2]. The primary environmental benefit of SAF lies in its potential to reduce lifecycle carbon dioxide (CO_2) emissions by up to 80 % compared to traditional jet fuel, depending on the specific production process employed [1]. This reduction is achieved by replacing fossil carbon with carbon that has been absorbed from the atmosphere during the growth of the biomass feedstock, thus closing the carbon cycle. Additionally, SAF production pathways contribute to lower particulate matter emissions and sulfur oxides. According to the IATA study, the SAF is expected to achieve the highest CO_2 emission reductions of all the plans, contributing to 24–70 % (with a median of 53 %) CO_2 emission reductions in 2050 compared to the corresponding baseline emission levels [3]. Considering these challenges, recent studies have underscored the pressing need for the aviation sector to adopt more sustainable practices. Klöwer [4] has further quantified aviation's contribution to global warming, emphasizing this urgent need. One promising solution highlighted by leading industry players is the integration of SAF. According to Airbus, SAF is critical for achieving significant reductions in greenhouse gas emissions, aligning closely with international environmental policies, and thereby facilitating a transition towards a more sustainable aviation industry [5]. Additionally, Ryanair's recent agreement [6] with Repsol to promote the use of SAF across its fleet exemplifies the industry's growing commitment to sustainable practices. This agreement not only underscores the potential of SAF to reduce emissions but also sets a benchmark for other airlines to follow.

According to Airbus, the integration of Sustainable Aviation Fuel (SAF) is a critical step towards achieving the aviation industry's environmental goals. Airbus emphasizes that the deployment of SAF can significantly reduce greenhouse gas emissions, thus aligning with the broader objectives of international environmental policies [5]. Additionally, the IATA's Fly Net Zero [7] initiative highlights the importance of adopting SAF as a key component in the aviation sector's strategy to reach net-zero emissions by 2050. This initiative underscores the necessity for both regulatory support and technological advancements to facilitate the widespread use of SAF in aviation operations, showcasing the industry's commitment to sustainable practices. Additionally, the European Union Aviation Safety Agency (EASA) has been proactive in its efforts [8] to harmonize fuel and energy planning policies across airlines, as demonstrated by Lufthansa's comprehensive implementation strategy. This strategy includes detailed fuel consumption monitoring and in-flight fuel management policies that are crucial for maximizing SAF efficiency. The alignment with ICAO's sustainable fuel policies [9] further reinforces the long-term benefits of such strategies. Continued support from regulatory frameworks and policy incentives will be crucial in overcoming these challenges [10].

A detailed report by Booz Allen Hamilton [11] underscores the economic impact of business aviation on the European economy. The report highlights that business aviation significantly contributes to job creation, regional development, and economic activity, especially in regions with limited commercial air services. Pazourek [12] emphasizes the unique operational characteristics and economic contributions of business aviation in Europe. Despite the smaller size of business aviation compared to commercial airlines, it plays a vital role in regional connectivity and economic activity. The importance of these considerations is underscored by the resilience of the business aviation sector during the COVID-19 pandemic. According to a systematic literature review by Pantelaki and Papatheodorou [13], this resilience highlighted the sector's significant contributions to travel efficiency, regional connectivity, and emergency services, which are crucial for both business and societal functions. As such, there is a growing body of research focusing on the sustainability of business aviation, with a particular emphasis on the integration of SAF to reduce environmental impact.

However, the integration of SAF must also consider the broader economic implications within the aviation network. In this context, the role of the market becomes particularly relevant. The travel patterns of the customers are indicating that their preference for private jets is driven by the need for privacy, flexibility, and efficiency. Furthermore, a detailed study on business jets [14] reveals that the wealthiest segments of society, who frequently utilize business aviation, have a substantial role to play in the adoption of SAF, as it is assumed that this passenger segment has more financial capacity to absorb the higher costs associated with SAF but also the potential to lead by example in reducing the aviation sector's carbon footprint. Encouraging this segment to adopt SAF could thus play a pivotal role in accelerating the transition towards more sustainable aviation practices industry-wide [15]. By leveraging influence, business aviation customers can set a precedent for broader acceptance and utilization of SAF across the industry.

The integration of SAF into existing aviation operations is heavily influenced by the legislative framework and regulatory standards that govern the aviation industry. Paper also deals with identifying the regulatory documents and guidelines that dictate the use of aviation fuels, particularly SAF, within both international and Czech contexts. The study reviews key international regulations set forth by bodies such as the International Civil Aviation Organization (ICAO) and the European Union Aviation Safety Agency (EASA), so that the analysis within this study aligns with the relevant regulations. These organizations provide frameworks that dictate everything from fuel standards and safety regulations to environmental compliance. Specific attention is paid to ICAO's CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation), which sets out emission reduction goals and sustainable fuel usage policies. EASA's guidelines on alternative fuels also play a crucial role in defining how SAF can be integrated into existing fleets without compromising safety and operational integrity. As part of the EU's commitment to reduce greenhouse gas emissions, the EU ETS (EU Emissions

Trading System) serves as a cornerstone mechanism, allowing for the trading of emission permits among companies and entities. It is a major tool used to regulate emissions from the aviation sector by setting caps on the total amount of greenhouse gases that can be emitted. Operators must hold permits equivalent to their emissions, and they can trade these permits to stay within legal limits [16].

In line with EU directives, Czech legislation incorporates these EU regulations into its national laws, primarily through Act No. 383/2012 on Conditions for Trading Emission Allowances. This law ensures that aviation operators within the Czech Republic are obliged to comply with EU ETS regulations and contribute to the national and EU-wide goals of reducing greenhouse gas emissions. Additionally, recent policy developments emphasize the need for robust support mechanisms to encourage SAF adoption, including incentives and subsidies [10].

EU ETS regulation provides an exemption for operators emitting less than 10 000 tonnes of CO_2 annually, which is nowadays a reason why many operators focus on never exceeding this emissions threshold so that they are not required to pay for emission allowances. However, the proposed changes under the "Fit for 55" package suggest that this exemption is likely to be reduced or eliminated in the near future. As the EU intensifies its efforts to meet its climate targets, smaller operators should prepare for increased regulatory and financial obligations related to their emissions. The shift signals a significant step towards a more inclusive and stringent emissions trading system, reflecting the broader goals of environmental sustainability and climate change mitigation. This might be the most significant reason why adaptation of SAF could be a solution for business aviation operators as flights on SAF will not produce the same amount of CO_2 as flying on fossil fuels which will lower operator's emissions costs. On the other hand, current prices of SAF are higher than JET A-1 fuel so the pricing of SAF will be crucial factor for new fueling strategies of operators.

Within this framework, the Czech Republic's burgeoning business aviation sector represents a key area of focus. This sector, while smaller than commercial airlines, significantly impacts environmental sustainability due to its specific operational characteristics and fuel usage patterns, and is often targeted due to significantly higher CO_2 emission per passenger/km, than commercial flights. Business aviation in the Czech Republic, characterized by its flexibility and personalized services, faces unique challenges and opportunities in adopting SAF. This study addresses these by first outlining the current state of SAF technology and its global adoption, highlighting advancements in fuel technology, regulatory incentives, and the economic rationale behind its adoption. The introduction of SAF not only promises to reduce the sector's greenhouse gas emissions but also aligns with global regulatory trends favoring greener alternatives.

The objectives of this research are twofold: to provide a detailed analysis of the operational network characteristics of Czech Registered Business Aircraft operator, assessing how these can be optimized to facilitate the transition to SAF; and to evaluate different refueling strategies, such as Minimum Fuel and Maximum SAF Refueling Strategies, for their environmental and economic efficiency. By offering a comprehensive overview and strategic recommendations, this study aims to contribute to the ongoing discussion on sustainable aviation practices and assist stakeholders in making informed decisions regarding the adoption of SAF.

Further, this paper investigates the specific needs and feasibility of integrating SAF into the operator's network. It examines the logistical considerations, including the availability of SAF, the infrastructure required for its distribution, and the potential for retrofitting existing aircraft or acquiring new ones compatible with SAF. It also considers the economic implications, analyzing the cost differentials between SAF and conventional fuels and evaluating the financial impact of potential regulatory changes, such as carbon pricing or emissions trading schemes that could favor SAF adoption.

2. Materials and methods

This section of the paper delineates the comprehensive methodological framework utilized to examine the integration and implications of SAF within Czech Registered Business Aircraft operator. To systematically assess the potential of SAF, the methodology is organized into several pivotal areas that build upon each other to form a cohesive analysis. The research begins by examining the characteristics of the carrier's network, which lays the foundational understanding of the current operational context and identifies key areas where SAF could be integrated effectively. This initial analysis helps in mapping out the operational scope and identifying specific routes and hubs that could benefit from SAF.

Following the network analysis, the study transitions into defining and applying relevant regulations and standards that govern the use of alternative fuels in aviation. This includes exploring both international guidelines and local regulatory frameworks that influence fuel choices, safety standards, and environmental compliance. These regulations set the parameters for what is feasible within the current legal and operational boundaries and help in shaping the refueling strategies that will be explored.

With a clear understanding of the operational context and regulatory constraints, the methodology then delves into the specific refueling strategies. This stage involves a detailed examination of different approaches to integrating SAF into the carrier's fuel supply chain, assessing the logistical, economic, and environmental implications of each strategy. It is at this point that the study evaluates the feasibility of two strategies, setting the stage for a deeper investigation into the environmental and economic impacts of each approach.

Finally, the methodology addresses the attributes for calculating emissions and costs, which are crucial for quantifying the benefits and challenges of adopting SAF. This includes detailed calculations of fuel consumption, CO_2 emissions, and cost analysis, providing the empirical data necessary to support decision-making. These attributes are essential for assessing the viability of SAF from a sustainability perspective and its alignment with business objectives. Each of these areas is integral to a thorough evaluation of SAF's feasibility and impact on operations, and together they provide a structured approach to understanding how SAF can be realistically and beneficially integrated into Czech business aviation. The subsequent sub-sections will delve deeper into each of these areas, offering a detailed exploration of the methods and tools used, the data gathered, and the analyses conducted.

The analysis begins with calculating the fuel consumption for each flight segment, considering different aircraft types and their specific fuel consumption rates. Data is collected according to the average fuel consumption per one hour flight, and adjustments are made based on whether SAF or conventional jet fuel is utilized. The efficiency of SAF in terms of energy content compared to Jet A-1 is also evaluated to determine if there are any significant differences in the amount of fuel required for similar flight operations.

2.1. DATA COLLECTION

The initial phase of the methodology focuses on the comprehensive collection of data were provided, containing information on 2 400 flights over the course of one year. The data included departure and arrival airports, flight duration, aircraft type, and specific fuel consumption details for the company's aircraft. Using the provided data, fuel consumption was calculated for individual flights. In the following step of the methodology, as described in Section 2.2, SAF was theoretically integrated on selected routes according to the refueling strategies detailed in Section 2.3. Airport information, provided in IATA codes, was specifically used to identify airports for theoretical SAF integration, while flight duration and aircraft type were employed to calculate fuel consumption. This data was supplemented by interviews with professionals from business aviation and flight operations personnel to gain insights into operational nuances that standard data collection might overlook. The purpose of this rigorous data collection process is to ensure that the study has a robust dataset that accurately reflects the real-world operations of the carrier, which is essential for a valid analysis.

2.2. NETWORK ANALYSIS: CONNECTIVITY EVALUATION USING GEPHI

The connectivity analysis is specifically used to select the most frequented airports within the network. These airports are chosen based on their high traffic volumes and strategic importance to the overall network efficiency and service quality.

After collecting the necessary data, the study utilizes Gephi, an advanced network analysis tool, to evaluate the connectivity of the carrier's network [3]. This tool allows for the visualization and analysis of the relationships and flows between different nodes within the aviation network, such as airports, flight routes, and aircraft movements. By analyzing the operational data with Gephi, the research identifies key nodes (major hubs) and links (frequent routes) with the highest potential for the effective integration of SAF.

This detailed connectivity analysis is instrumental in developing tailored refueling strategies. By focusing on the most active airports, the study ensures that the strategies developed are relevant and impactful, providing valuable insights into how SAF could be realistically integrated into the existing operational framework. Based on the connectivity analysis, five of the most frequently serviced airports were selected for theoretical SAF integration. This number was set as an illustrative value within which the model's results will be assessed. This value can be adjusted based on the actual availability of SAF at the airports. Currently, SAF infrastructure is more tied to large airports that are hubs for fleets of legacy carriers such as British Airways, Lufthansa, KLM, joined by Nordic region Copenhagen and Stockholm Arlanda airports.

2.3. REFUELING STRATEGIES

Methodology elaborates on two refined refueling strategies tailored to assess the viability of SAF in different operational scenarios based on data provided by one specific Czech Registered Business Aircraft operator. These strategies will be described below as Model 1 for Minimum Refueling Strategy and Model 2 for Maximum SAF Refueling Strategy.

Both models assume the integration of a 40 % SAF blend, with 60 % Jet A1 at the same five airports, based on the results of the network analysis. This is based on the availability and current regulatory acceptance of such blends for commercial use. This blend ratio is considered to be a practical and realistic option for testing within the existing infrastructure because it does not require significant modifications to aircraft engines or fuel distribution systems. Additionally, a 40 % blend is within the range that can substantially reduce carbon emissions while still ensuring optimal engine performance and fuel availability.

In both models, the volume of fuel burned is used as an input numerical value, and this value remains consistent between the two models. Although Model 2 would typically be expected to show a higher fuel burn due to the added weight of fuel associated with fuel tankering. This factor has been excluded in order to focus on illustrating the core aspects of the model. However, these, so called tankering fuel penalties (additional fuel burnt due weight of fuel itself) were not considered in the calculations to maintain the simplicity of a foundational model, as it was deemed outside the primary scope of analysis. Industry estimates suggest penalties of around 0,33 % fuel burn penalty per 100 km [17], but the actual penalty can vary depending on aircraft type, payload, flown distance and other variables.

The practice of fuel tankering or carrying excess fuel is utilized in the Model 2 to maximize the use of SAF. This approach intentionally increases SAF usage despite its potential drawbacks, reflecting a calculated trade-off to boost the share of sustainable fuel in the fleet's fuel blend. This decision underscores the commitment to integrating SAF more extensively, even if it involves temporary increases in overall fuel consumption, to achieve long-term sustainability goals in business aviation [2].

Given the nature of the data, it is not possible to include potential diversions to alternate airports or other events that would lead to the consumption of a certain amount from the fuel reserve in the calculation. The diversions however pose only 0,3 % of cases on average and therefore are not so significant [18]. Data regarding diverts or change of routes due to the weather were not provided for this analysis. However, this model does not work with operational specifics such as the lengths of RWY at individual destinations. Therefore, possible operational limitations for aircraft weight were not taken into account in creating the model.

Model 1 For Model 1 (Minimum Refueling Strategy), it is specified that the operator only fills the minimal amount of fuel necessary for the next segment at each landing airport. Therefore, Model 1 operates with the assumption that each landing leaves exactly this amount of fuel of 600 kg, known as "Final Reserve Fuel", in the tanks. In Model 1 the operator fills SAF at the five most frequently serviced airports according to the network analysis. At other destinations, JET A-1 is filled. For clarity, a decision tree is created, which describes the refueling variants typical for Model 1, see Figure 1.

Model 2 Model 2 (Maximum SAF Refueling Strategy) works with the version where the operator fills SAF at the five most frequently serviced airports to the maximum possible volume. At other destinations, the operator fills JET A-1, but always only adds as much as is necessary to service the next segment. This means that if the operator fills with SAF fuel, therefore to the full, and only a short segment follows, no fuel needs to be refilled if there is no SAF at this destination and there is a sufficient amount of fuel in the tanks from the previous flight. If SAF fuel was available at this destination, the operator would again fill to the maximum possible amount. The decision tree for Model 2 is evident in Figure 2.

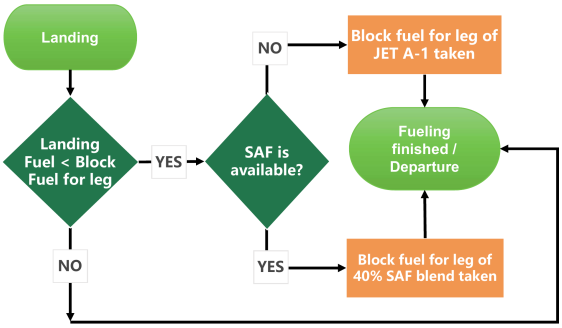

Figure 1. Model 1 – Minimum Refueling Strategy.

2.4. Formulas and figures

By offering a comprehensive overview and strategic recommendations, this study aims to contribute to the ongoing discussion on sustainable aviation practices and assist stakeholders in making informed decisions regarding the adoption of SAF. The two main variables resulting from both models that will help in decision making are fuel costs and total emissions. The use of SAF reduces total emissions, however, it increases overall fuel expenses due to the higher production costs associated with SAF compared to conventional Jet A-1.

The fuel costs C when using SAF are calculated using the formula:

$$C = [(1 - F_{40})P_{JET} + F_{40}P_{SAF}]\, m, \qquad (1)$$

where:

F_{40} is the proportion of 40 % SAF in the total fuel consumption,

P_{JET} is the unit price in EUR per 1 kg of JET A1 fuel,

P_{SAF} is the unit price in euros per 1 kg of 40 % SAF,

m is the total weight of fuel consumed.

The total emissions E when using SAF are calculated according to the formula:

$$E = [(1 - F_{40})E_{JET} + F_{40}E_{SAF}]m, \qquad (2)$$

where:

F_{40} is the proportion of 40 % SAF in the total fuel consumption,

E_{JET} is the unit emissions in kg CO_2 per kg of burned JET A1 fuel,

E_{SAF} is the unit emissions in kg CO_2 per kg of burned 40 % SAF blend fuel,

m is the total weight of fuel consumed.

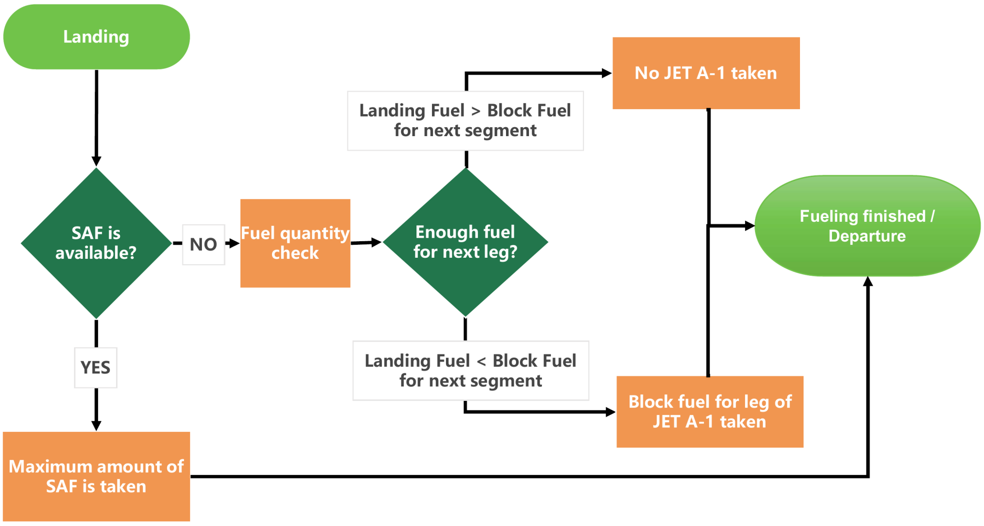

FIGURE 2. Model 2 – Maximum SAF Refueling Strategy.

According to the results of Model 1 and Model 2 above, all the input parameters to the equations can be determined. Based on the results of Model 1 and Model 2 and by applying the above mentioned formulas, the following values will be presented in the Results section: Emision reduction [%], share of SAF integrated [%], Total fuel consumption [kg], Total fuel costs with SAF integrated [€], Fuel cost of JET A-1 [€], Increased fuel cost caused by SAF integration [€], CO_2 emissions with JET A-1 only [kg], CO_2 emissions with SAF integrated [kg], CO_2 reduction achieved through SAF integration [kg], and price increase per flight hour [€].

2.5. ATTRIBUTES FOR CALCULATING EMISSIONS AND COSTS

A critical aspect of this study is the calculation of emissions from both SAF and conventional fuels. For this calculation, the emissions factor is the most fundamental element. The emission factor of fuel refers to the amount of emissions produced per unit of fuel consumed. It is a key metric used to estimate and compare the environmental impact of different fuels. Emission factors are typically expressed in terms of mass of CO_2 (or CO_2 equivalent for other GHGs) emitted per unit of energy (e.g., kilograms of CO_2 per gigajoule) or per unit of fuel (e.g., kilograms of CO_2 per liter or per kilogram of fuel). In this paper emission factor describe mass of CO_2 per one kilogram of burned fuel. Emissions of carbon dioxide differs (CO_2) for each type of fuel. The carbon emissions are particularly important, as one of the main advantages of SAF is its potential to reduce lifecycle carbon emissions compared to conventional fuels. Factors such as the blend ratio of SAF with conventional fuel and the specific emission factors associated with each type of fuel are considered. The emission factor for JET A1 is 3.15 kg CO_2 per kg of fuel burned [19]. This factor reflects the typical carbon emissions associated with the combustion of conventional jet fuel. For 40 % SAF blend, the emission factor used is lower, at 2.55 kg CO_2 per kg of fuel burned. This lower emission factor is due to the reduced carbon content of SAF, which is made from renewable sources that can absorb CO_2 during their growth phase, offsetting some of the emissions produced during fuel combustion. This property of SAF contributes to its potential to reduce the overall carbon footprint of aviation fuel when compared to conventional jet fuel.

The cost of fueling aircraft with SAF versus conventional jet fuel forms a significant part of the economic analysis. This includes the per-liter cost of each type of fuel, potential changes in maintenance costs due to different fuel properties, and the amortization of any additional infrastructure investments required for storing and handling SAF. In addition, potential economic incentives such as tax rebates, emission trading credits, or subsidies for using SAF are analyzed to determine their impact on the overall cost-effectiveness of SAF adoption. Jet A-1 fuel price was set at $€\,0.73\,\mathrm{kg}^{-1}$. This price was quoted for the Europe and CIS region (Commonwealth of Independent States) as of April 2023 [20]. A price of a 40 % SAF blend, was used at $€\,2.5\,\mathrm{kg}^{-1}$, which is the price listed for Amsterdam Schiphol Airport (EHAM) as of April 2023. This reflects the common estimation that SAF is typically 2–6 times more expensive than Jet A-1. Based on an analysis of the current market, it can be concluded that current prices are comparable.

3. RESULTS

For both refueling strategies, this section outlines the fundamental parameters that shape the operational, economic, and environmental aspects of integrating SAF into the fleet operations of a business aviation operator. The results will be presented in the structure defined in Section 2.4.

Emissions reduction	5.5 %
Share of SAF integrated	11,5 % of total fuel
Total fuel consumption	3 353 469 kg
Total fuel cost with SAF integrated	4 158 806 €
Fuel cost of JET A-1	2 448 032 €
Increased fuel cost caused by SAF integration	1 710 774 €
CO_2 Emissions with JET A-1 only	10 563 427 kg
CO_2 Emissions with SAF integrated	9 983 503 kg
Reduction of CO_2 with SAF integrated	579 923 kg
Price Increase per Flight Hour	146 €

Table 1. Model 1 – Minimum Refueling Strategy – results.

3.1. Model 1 – Minimum Refueling Strategy

Under the Minimum Refueling Strategy incorporates a 40 % SAF blend at the five most frequently served destinations, filling the minimum required fuel for the next leg. In this case, the operator will save 5,5 % of emissions. Pure SAF constitutes 11,5 % of the total fuel which operator consumed per one year. The total fuel consumption is 3 353 469 kg. Regarding fuel acquired data, the operator would face a fuel cost of about € 2 448,032 for a JET A-1-only flight. If the 11,529 % of pure SAF will be integrated, the fuel cost would rise to € 4 158 806, exceeding the fossil fuel-only cost by € 1 710 774.

The economic impact, whether positive or negative, would depend on the individual pricing of flights. The pricing in business aviation is influenced by various factors, such as airport charges, flight length, cross-country charges, and departure times. It cannot be definitively stated whether the model application would have a positive or negative economic impact on the operator. However, in a simplified analysis, the increased costs per flight hour could be budgeted. If the operator would like to compensate the increased costs using this model, it would need to raise the price per flight hour sold by an average of € 146.

If all flights were operated on JET A-1 fuel with an emission factor of 3.15 kg CO_2 kg^{-1} fuel, the total CO_2 produced per year would be 10 563 427 kg. This exceeds the 10 000 tonnes CO_2 limit, necessitating the purchase of emission allowances. It was found that by incorporating SAF flights according to the Minimum Refueling Strategy outlined in Model 1, the operator would emit 9 983 503 kg of CO_2. This places them just below the threshold, eliminating the obligation to purchase emission allowances. The model has a positive environmental impact, reducing CO_2 emissions by 579 923 kg compared to identical flights using JET A-1 fuel alone. Summary of results in Table 1.

3.2. Model 2 – Maximum SAF Refueling Strategy

In the Maximum SAF Refueling Strategy, instead of always refueling the volume required for the next flight, the operator fills the maximum possible amount of 40 % SAF blend at the five SAF destinations. Then, if the operator operates from a destination where SAF is not available, they take only the minimum amount of JET A-1 fuel to safely depart for the next leg. Applying this strategy, the operator will save 12,7 % of emissions. Pure SAF constitutes of 26,573 % of the total fuel which operator consumed per one year. The total fuel consumption is 3 353 469 kg. If the entire operation were to operate with JET A-1 fuel only, the fuel cost is € 2 451 583. When using SAF, the cost would be € 6 400 570. This strategy would, therefore, increase the fuel cost by € 3 948 987 per year.

As mentioned in the analogous section for Minimum Refueling Strategy, only the operator's pricing strategy will determine whether the increased costs would be offset by the extra flight hours gained. Then, if the operator would like to compensate the increased costs using Model 2 by increasing the price per hour sold, the price would increase by € 610 per flight hour.

If all flights were operated on JET A-1 fuel with an emission factor of 3.15 kg CO_2 kg^{-1} fuel, the total CO_2 produced per year would be 10 563 427 kg. This also exceeds the 10 000 tonnes CO_2 limit, necessitating the purchase of emission allowances. It was found that by incorporating SAF flights as per the Maximum SAF Refueling Strategy described by Model 2, the operator would emit 9 240 108 kg of CO_2. The model has a positive environmental impact, reducing CO_2 emissions by 1 338 640 kg of CO_2 compared to identical flights using JET A-1 fuel alone. Summary of results in Table 2.

4. Discussion

The integration of SAF in business aviation involves a complex interplay of economic costs, operational changes, and environmental impacts. The two models developed in the paper encapsulate different strategies for integrating SAF, highlighting the practical considerations and potential outcomes from such initiatives. These models serve as a foundation for understanding the broader implications of SAF adoption within the sector.

Model 1 uses a conservative approach by incorporating a 40 % SAF blend at the five most frequently

Emissions reduction	12.7 %
Share of SAF integrated	27 % of total fuel
Total fuel consumption	3 353 469 kg
Total fuel cost with SAF integrated	6 400 570 €
Fuel cost of JET A-1	2 451 583 €
Increased fuel cost caused by SAF integration	3 948 987 €
CO_2 Emissions with JET A-1 only	10 563 427 kg
CO_2 Emissions with SAF integrated	9 240 112 kg
Reduction of CO_2 with SAF integrated	1 338 640 kg
Price Increase per Flight Hour	610 €

TABLE 2. Model 2 – Maximum Refueling Strategy – results.

served destinations, filling the minimum required fuel for the next leg. This strategy aims to optimize operational efficiency while adhering to environmental regulations. Financially, this model necessitates an increase in fuel costs due to the higher price of SAF compared to conventional jet fuel. Despite the increase in fuel expenditure, the implementation of SAF under Model 1 would lead to a reduction in CO_2 emissions by 5.5 %. The model suggests a potential reduction in CO_2 emissions by keeping the total emissions just below the threshold that would require the purchase of additional emission allowances. This aspect alone could provide a cost-saving benefit, offsetting some of the increased fuel costs. Furthermore, recent ICAO findings support that SAF can significantly lower lifecycle emissions, making it a viable option for meeting stringent environmental targets [9].

Model 2 proposes a more aggressive use of SAF, maximizing the amount of SAF used at every opportunity where it is available, and only supplementing with Jet A-1 where necessary. This model is designed to push the boundaries of how much SAF can be integrated into current operations without altering the core functionalities of aircraft or requiring significant changes in infrastructure. The analysis shows that while Model 2 leads to higher upfront costs due to the increased consumption of more expensive SAF, it also maximizes the environmental benefits. The higher expenditure on SAF could potentially be mitigated by the savings from not having to buy emission allowances, as the reduced CO_2 production keeps the total emissions below critical regulatory thresholds.

Both models underscore the practical challenges of cost management and operational adjustments required for transitioning to SAF. They reflect the ongoing need for strategic planning in business aviation to balance cost, operational feasibility, and environmental responsibility. The introduction of SAF, despite its higher cost, presents an opportunity to significantly reduce the environmental footprint of aviation operations, aligning with global sustainability goals.

Certain limitations were intentionally applied in this study to maintain a fundamental model that is both illustrative and straightforward, enabling future expansions. Key simplifications include disregarding the increased fuel consumption associated with tankering and omitting the variability in the sustainable component ratio of SAF, which is legislatively mandated to range from 2 % to 6 % in upcoming periods. Additionally, while current regulations allow for up to 50 % SAF usage, flights with 100 % SAF have also been conducted, adding another layer of potential complexity. Another limitation is the omission of variability in the emissions factor, which can vary significantly. These constraints were applied solely to ensure the model's clarity and simplicity, creating a clear baseline that future studies can build upon by incorporating additional variables for a more comprehensive analysis.

However, the real-world application of these models would require careful consideration of fuel price volatility, the availability of SAF, and the specific operational profiles of different airlines with weather information or data about diversions. As the industry moves towards more sustainable practices, these models provide a framework for understanding the potential costs and benefits of integrating SAF but highlight the necessity for adaptive management strategies that can respond to changing economic conditions and regulatory landscapes. The broader adoption of SAF is supported by evolving policies [10] and incentives designed to facilitate a smoother transition towards more sustainable aviation.

5. CONCLUSIONS

This study has thoroughly investigated the potential integration of Sustainable Aviation Fuel (SAF) in business aviation, emphasizing its economic and environmental implications. The research has demonstrated that while SAF presents opportunities for significant reductions in carbon emissions, its integration within business aviation faces various challenges, including higher costs and limited availability.

Key findings highlight that adopting SAF can lead to considerable environmental benefits by reducing the carbon footprint of business aviation operations. However, the economic impact of integrating SAF involves increased fuel costs, which are influenced by the current higher prices of SAF compared to conventional Jet A-1 fuel. Despite these costs, the potential savings from reduced carbon emissions and the avoidance of emissions trading costs under schemes like the EU ETS could offset some of the financial burdens.

The analysis of two refueling strategies – Minimum Fuel and Maximum SAF Refueling Strategies – provided insights into the operational adjustments necessary to accommodate SAF. These strategies, though distinct, both align with the global push towards sustainability and comply with emerging environmental regulations. They also illustrate the trade-offs between achieving maximum environmental benefits and managing operational and financial realities.

The research underscores the need for further development in SAF production and distribution to make it more accessible and economically viable for business aviation. It also calls for continued regulatory support to foster the adoption of SAF, including incentives that could mitigate the high costs associated with its use. ICAO's ongoing efforts in promoting SAF adoption highlight the importance of international cooperation in achieving these sustainability goals.

Ultimately, this study concludes that while the integration of SAF into business aviation is fraught with challenges, it remains a critical component of the industry's journey towards sustainability. The findings of this study contribute to the broader discourse on sustainable aviation practices, offering valuable insights for operators, policymakers, and researchers aiming to advance the use of sustainable fuels in aviation.

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