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Analysis of CO2 Emissions and Cost Resulting from the Adoption of Sustainable Aviation Fuels by Medium Range Aircraft in Different World Regions

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Abstract. This paper aims at evaluating the potential impact on CO2 emissions and cost as result of the exploitation of different kinds of SAFs, around different regions of the world. The study focuses, on one side, on the life-cycle emissions of the fuel, from production to aircraft operations, considering medium range flights from main hubs in Europe, United States, Brazil and Australia. This analysis makes benefit from a literature review on SAF producers around the world. The study of production processes allows in fact to identify the predicted life-cycle emissions of the specific fuel blend, up to the operational phase, also thanks to the adoption of the ICAO Carbon Emissions Calculator (ICEC). In parallel, an assessment of the cost associated to the use of SAF is also carried out, in comparison with conventional kerosene, along the years, up to 2050. Previsions on cost-per-kg of the different fuels are provided, taking into account the impact of the improvement of production process and increase of production quantity, together with inflation. The study demonstrates that, even if an increase of cost-per-kg for the fuel is always present, according to the predicted scenarios, the cost associated to the abatement of CO2 through the exploitation of SAFs has the potential of matching the equivalent cost of CO2 quotas in case an equivalent EU Emissions Trading System (ETS) is present, also considering the reduction of direct emissions over SAF lifecycle.

Introduction

Aviation de-carbonization has been an increasing worldwide effort for many years. In fact, even though commercial aircraft operations account for only 2% of global CO2 emissions, and 10% of overall transport means [1], their contribution is expected to grow due to the increase in traffic demand. During the last decade, also as result of the goals identified within the 2015 COP 21 Paris Agreement [2], the progressive reduction of CO2 emissions has been formalized within a roadmap named Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [3] by the International Civil Aviation Organization (ICAO), being in line with net-zero 2050 objective of the Long Term Aspirational Goal (LTAG) [4] proposed by the Committee on Aviation Environmental Protection (CAEP). As demonstrated in [5], emissions reduction can be achieved by introducing new aircraft and powerplant technologies, new fuels, as well as improved operations and Air Traffic Management (ATM). Notably, the most relevant contribution to de-carbonization is associated to the introduction of new fuels capable of either reducing their carbon footprint acting on a more sustainable life-cycle, while maintaining similar operations. This challenge can be actually addressed exploiting the so-called Sustainable Aviation Fuels (SAFs), most of which are produced thanks to organic feedstocks (biofuels) or advanced technologies associated to renewable energy sources and carbon-capture strategies (synthetic fuels), which can replace conventional kerosene (Jet A) as drop-in blends.

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Worldwide fleets are dominated by single-aisle short and medium range aircraft (70%), mostly flying along 2000 km routes [6]. This accounts for 65% of CO2 emissions of global aviation, while wide-body airliners flying long-range represent 30%, followed by regional and commuter services [6]. Acting on medium range aircraft is thus the priority to start make the difference. Notably, in the European market, the ReFuel EU plan [7], as part of "Fit for 55", aims at progressively substituting traditional kerosene with SAF in the amount of 2% by 2025, 6% by 2030 and 70% by 2050, which are considered mandatory targets for the airlines.

In this context, this paper aims at evaluating the potential saving in CO2 emissions as result of the exploitation of different kinds of SAFs, according to feedstocks and production processes, around different regions of the world. The study focuses on the life-cycle emissions of the fuel, from production to aircraft operations, considering medium range flights from main hubs in Europe, United States, Brazil and Australia. The work makes benefit from a literature review on SAF producers around the world, and it includes a brief analysis of the most promising production processes. On the other hand, the ICAO Carbon Emissions Calculator (ICEC) [8] is adopted to quantify the emissions for the flights considered within the study.

In parallel, an assessment of the cost associated to the use of SAF is also carried out, in comparison with conventional kerosene, along the years, up to 2050. Previsions on cost-per-kg of the different fuels are provided, leveraging information coming from the literature. A trade-off between emissions and cost is provided, with reference to the competitiveness of the exploitation of SAFs for CO2 abatement process in terms of cost per equivalent CO2 emission, if compared to traditional CO2 mitigation measures based on EU Emissions Trading System (ETS).

After this introduction, a methodological section is presented in order to describe the approach used for the determination of traffic demand for medium-range flight over different regions, as well as to present the results of the review about most adopted SAFs production processes around the globe, and related emissions/costs, hypothesizing a worldwide increase in SAF share according to the ReFuel EU-like plan. Then, a results section is provided to show the outcome of this analysis, also combining the data about emissions and cost in order to assess the competitiveness of SAFs adoption to comply with CO2 mitigation constraints if compared to the use of EU ETS. A summary section concludes the paper, paving the way for future works.

Methodology

As starting point of the workflow, an estimation of traffic demand is performed looking at the world regions previously specified (i.e. Europe, United States, Brazil and Australia), respectively in 2025, 2030 and 2050. The time span is selected in order to be in line with the goals of a ReFuel EU-like plan. References and literature models [9-10] are used in order to derive average traffic in million flights per year, as indicated in Table 1, looking at medium-range category.

Table 1: Hypotheses on traffic data (million flights per year)

Region	2025	2030	2050
Europe	2.02	2.24	2.67
USA	4.77	5.37	7.78
Brazil	0.32	0.44	0.93
Australia	0.66	0.72	1.01

Then, a set of relevant city pairs connected through medium-range flights is selected according to the information provided in [11], in order to consider the most representative missions for each world region. As result, an average value of distance vs fuel consumption is derived, taking into account a constant energy per unit mass of the fuel, equal to 43 MJ/kg, independently from the blend actually used (SAFs and conventional kerosene have very similar lower heating values). Results of this approach are shown in Table 2.

Table 2: Average fuel quantity for medium range flight in different regions

	Europe	USA	Brazil	Australia
Fuel quantity per flight [kg]	10,685	11,800	10,310	11,000

Moreover, a literature review about the main SAFs producers and production processes around the world is performed, with the aim of determining the most relevant SAFs categories in the different regions and the related feedstocks used for the production. This step is crucial since emissions associated to fuel lifecycle are very specific depending on the type of fuel, production process and feedstock, as well as on the actual region in which they are produced. As result, the data collected in Table 3 have been derived, looking at studies [12] and information provided in literature by the most relevant companies listed in [11].

Table 3: Emissions per unit energy for main SAF type produced in different regions

Region	Emissions per unit energy [gCO2eq/MJ]	(Fuel type) Feedstock
Europe	19.51	(HEFA) – Agricultural residues, used cooking oil, fatty acid distillate
USA	24.54	(ATJ) – Switchgrass, muscanthus, corn grain, sugarcane
Brazil	44.48	(ETJ) – Forestry residues, corn grain, sugarcane
Australia	23.64	(ATJ) – Switchgrass, muscanthus, poplar, forestry residues, agricultural residues

Resulting emissions per unit energy (gCO2eq/MJ) of the different fuels take already into account production phase as well as operations (i.e. combustion), so they can directly be used for the estimation of the overall lifecycle emissions when applied to the operational context specified in Table 2 (since they are proportional to the quantity of fuel used). Emissions per unit energy can be compared with the standard value of 89 gCO2eq/MJ traditionally adopted for Jet A. As it can be seen, SAF are around 20 – 25 gCO2eq/MJ in most regions, benefitting from the adoption of feedstocks for the production of HEFA or ATJ, with the exception of Brazil, where the use of forestry residues for ETJ production may strongly increase the carbon footprint.

The overall quantity of CO2eq produced during the lifecycle can be computed according to (1). The computation shall take into account the amount of SAF blend specified by ReFuel EU (ϕ) for 2025, 2030 and 2050, respectively equal to 2%, 6% and 70% of the total mixture.

In parallel to emissions evaluation, it is also important to assess the economic impact of SAF adoption, especially looking at the operational costs of blends.

$$kg_{CO2_{eq_{yr}}} = \left(\left(\frac{kg_{CO2_{eq}}}{MJ}\right)_{SAF} \cdot \phi_{yr} + \left(\frac{kg_{CO2_{eq}}}{MJ}\right)_{Jet\ A} \cdot (1-\phi_{yr})\right) \cdot \left(\frac{MJ}{kg}\right)_{fuel} \cdot m_{fuel_{flight}} \cdot n_{flights_{yr}} \quad (1)$$

According to the information present in [11-14], for the different world regions, considering the type of SAF described in Table 3, the costs reported in Table 4 apply for the different years used as reference in the study. The total Direct Operating Cost (DOC) for fuel can then be computed according to (2).

Table 4: Fuel cost [€/kg] in different regions

Years	Europe		USA		Brazil		Australia	
	Jet A	SAF	Jet A	SAF	Jet A	SAF	Jet A	SAF
2025	0.74	1.59	0.75	1.95	0.76	2.04	0.71	2.10
2030	0.77	1.41	0.78	1.73	0.80	1.73	0.75	1.89
2050	0.85	1.29	0.86	1.55	0.88	1.54	0.82	1.53

$$DOC_{fuel_{yr}} = \left(\left(\frac{€}{kg}\right)_{SAF_{yr}} \cdot \phi_{yr} + \left(\frac{€}{kg}\right)_{Jet\ A_{yr}} \cdot (1-\phi_{yr})\right) \cdot m_{fuel_{flight}} \cdot n_{flights_{yr}} \tag{2}$$

Ultimately, it is possible to relate costs and equivalent CO2 emissions for the different scenarios in order to estimate the cost associated to emissions reduction through the exploitation of SAFs. This relative cost (in €/kgCO2eq), specific for each year and world region, can be obtained by dividing the cost of fuel and the quantity of emissions, and it shall be computed incrementally, as differential cost, comparing the situation of the target year (i.e. the one under investigation) and a reference year (i.e. current situation or, in general, previous situation in which SAF exploitation is lower) in order to assess the viability of the solution. The mathematical relationship is shown in (3), where, for example, if the aim is to compute the cost per equivalent CO2 emission in 2030, if compared to the same value in 2025, taking into account aforementioned blend shares, i-th is 2030 and (i-1)th is 2025.

$$Cost_{CO2_{eq}} = \frac{DOC_{fuel_{yr_i}} - DOC_{fuel_{yr_{i-1}}}}{kg_{CO2_{eq_{yr_{i-1}}}} - kg_{CO2_{eq_{yr_i}}}} \tag{3}$$

In order to understand the cost-effectiveness of this measure, notwithstanding the obvious benefit in terms of absolute emissions, as specified in the next section, it is possible to compare the result with the relative cost of emissions abatement measures based on equivalent EU ETS. The cost of CO2 emissions on ETS-like quota allocation is also function of the related year, so an extrapolation of reference values used for this study are reported in Table 5 [5]. The application of ReFuel-EU-like plan as well as of an equivalent EU-ETS scheme is a strong hypothesis since different world regions would require specific policy making actions in order to obtain effective outcome, depending on the specific scenario.

Table 5: Reference value of cost for 1 tonn of CO2 in the EU ETS scheme

	2025	**2030**	**2050**
EU ETS – Cost per tonn of CO2 [€/tonn CO2]	78	101	188

The results in the next section shall then not be treated as universally applicable, but just as a starting point for the refinement of the theoretical approach.

Results

According to the methodology described in the previous section, total emissions trends per year, for the different world regions, can be shown in Fig. 1 (left). As it can be seen, after a couple of years, the adoption of SAF is generally beneficial for what concerns overall emissions quantity, expect for the Brazilian scenario, where the adoption of ETJ obtained from forestry residues do not ensure a positive abatement along the years. A similar trend summarizing the cost escalation due to the introduction of SAF blends, is shown in Fig. 1 (right), neglecting taxes. As it can be seen, the exploitation of SAF has a negative impact on cost, since a general increase is present, with differences depending on SAF types and world regions.

The cost-effectiveness related to CO2 compensation exploited through SAFs introduction, in comparison with conventional EU ETS scheme adoption for CO2 quota compensation, is shown in Fig. 2. As it can be seen, a progressive adoption of SAF may allow to match the expenses associated to CO2 compensation through equivalent EU ETS scheme with time. The breakeven point (i.e. where the different lines matches the cyan one) depends on the scenario considered for the different regions and the type of SAFs.

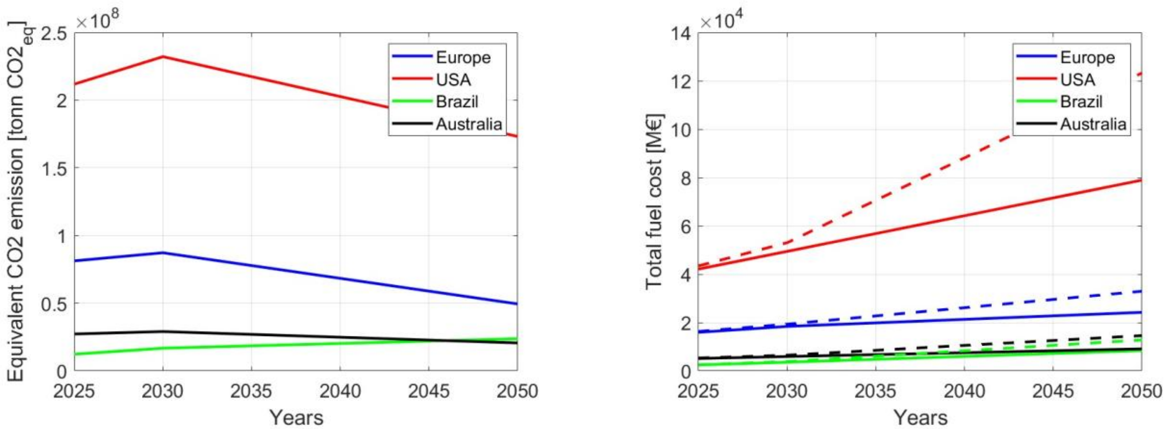

Figure 1: Total equivalent CO2 emissions (left) and total fuel cost (blends) (right) over the years

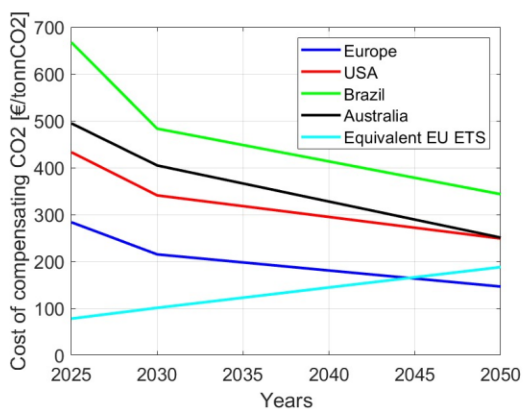

Figure 2: Cost per CO2 emissions and comparison between SAF adoption and EU ETS-like compensation

Summary

The methodology described in this paper demonstrates how to rapidly assess the impact of the progressive SAFs introduction in aviation on emissions and costs, according to international roadmaps, such as ReFuel-EU. The methodology is based on four main steps, consisting respectively in evaluation of traffic, analysis of SAFs production processes and feedstocks, assessment of cost associated to SAFs introduction and cost-effectiveness evaluation through the analysis of the trade-off between cost escalation and emissions reduction resulting from the increase in SAF blends over the years. Results demonstrate that different world regions shall be analyzed adopting different assumptions and policies, considering their specific needs and socio-economic situation. However, the results show that incremental introduction of SAFs in Europe can contribute, over the years, to a sensible reduction of CO2 emissions and that the cost associated to the introduction of new fuel can be competitive with reference to the traditional CO2 quota

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allocation based on EU ETS scheme in the long term. Future works shall deal with detailed analyses on different world regions, as well as with assessment of the principles behind the ETS-like schemes in order to improve the cost-effectiveness evaluation.

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