E-KEROSENE POTENTIAL FOR COMMERCIAL AVIATION DECARBONIZATION

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Abstract

Reducing greenhouse gas emissions from aircraft transport is crucial to achieving climate goals. In this sense, the present study looks into the suitability of e-fuels such as e-kerosene in reducing CO_2 emissions. The Fleet System Dynamic Model is employed to examine data and predict future trends in line with the Committee on Aviation Environmental Protection. While the findings suggest that achieving carbon-neutral growth is possible, it might take longer than current forecasts indicate. For instance, considering an e-fuel production rate of 15%, it is possible to cut emissions by half around 2060 concerning 2005 levels.

Keywords: E-fuels; CO_2 emissions; Aviation; E-kerosene

1. Introduction

Aviation is a necessary mode of transportation that ensures global connectivity. Air travel has doubled every fifteen to twenty years from the dawn of the jet era up to the COVID–19 pandemic [1]. According to the International Civil Aviation Organization (ICAO) [2], airline passenger traffic decreased by 60% in 2020 when compared to the previous year, causing losses of 372 billion USD in airline revenue. By the end of 2022, ICAO estimated a rebound in passenger affluence to 30% of 2019 levels (Figure 1), while in 2025, air passenger volume is expected to reach 111% of pre-pandemic values [3].

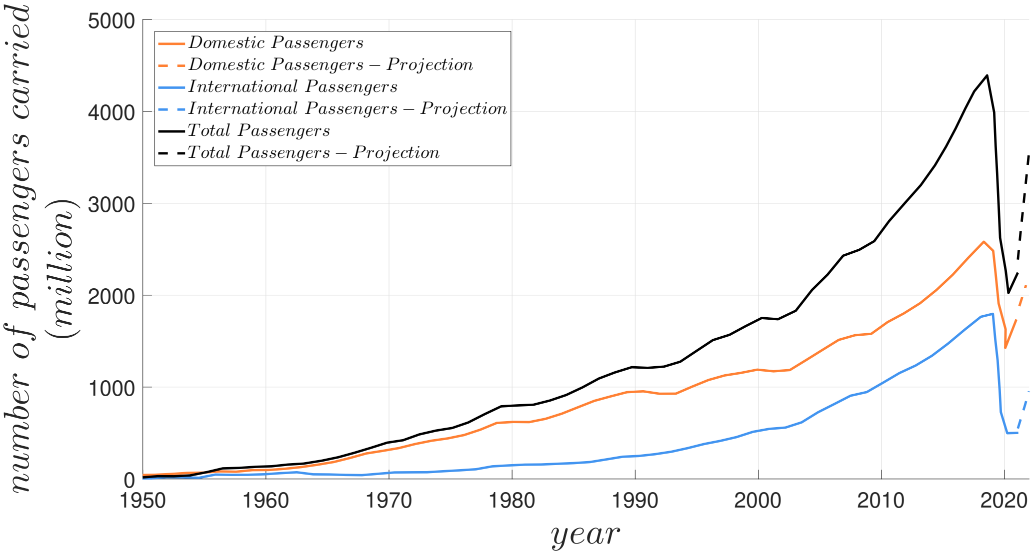


Figure 1 – Global passengers carried from 1945 until 2022 projections [4].

Decarbonizing the global economy across all sectors is imperative to limit global warming to 1.5° C. Enhancing energy efficiency, electrifying energy use, and transitioning to low-emitting electrical sources are pivotal measures for substantial emissions reduction. Numerous nations and businesses have committed to net-zero emissions targets. However, decarbonizing the aviation sector poses unique challenges due to its reliance on energy-dense liquid hydrocarbons and the non-CO_2 radiative forcing associated with flights [5]. Despite aviation generating less than 3% of global greenhouse gas emissions, they are increasing rapidly [6]. The aviation industry faces mounting pressure to curtail its carbon footprint, especially as the momentum toward carbon-neutral transportation grows. Additionally, the anticipated resurgence of commercial aviation traffic, surpassing pre-pandemic levels, underscores the urgency for emissions reduction [4].

The International Air Transport Association (IATA) anticipates a substantial surge in air travel demand, exceeding 10 billion individual air passenger journeys by 2050 [7]. As a consequence, CO_2 are projected to double by 2050 compared to 2020 levels. In response to this challenge, the Air Transport Action Group (ATAG), comprising fundamental stakeholders in the aviation industry, introduced Waypoint 2050. The primary objective is to achieve net-zero carbon emissions by 2050, relying on four key pillars: sustainable aviation fuels (SAFs); investments in new aircraft technologies; enhancements in air traffic management and infrastructure; and offsetting or out-of-sector carbon reductions [8]. IATA estimates that these concerted efforts could mitigate 21.2 Gt of CO_2 by the designated waypoint [7].

While the use of SAFs is advocated as a means to reach climate goals [9], relying solely on them may come up short of the target [10], given the projected expansion of the aviation sector. E-fuels in particular do not require biomass to produce liquid hydrocarbons offering a short/medium-term solution to achieve net zero emissions [4]. In the process of creating e-fuels, electricity is used to split hydrogen from oxygen. Hydrogen is then combined with carbon dioxide, which can be captured from the atmosphere or from industrial processes, to create a hydrocarbon molecule using a process called Fischer-Tropsch synthesis. Lastly, the hydrocarbon molecule is then refined to create an e-fuel that can be used in conventional combustion engines [11].

The reaction between CO_2 and H_2 offers a viable pathway for generating a diverse spectrum of fuels, ranging from low-carbon methane, ethane, and propane (Power-to-Gas) to commercially valuable liquid e-fuels like methanol and synthetic jet fuel (Power-to-Liquid) [12]. E-methanol can serve as a drop-in solution blended into conventional fuels up to 3% [13, 12, 14]. For longer-chained hydrocarbons like e-kerosene, e-diesel, e-gasoline, and synthetic aviation fuel, the power-to-liquid process relies on Fischer-Tropsch synthesis. Its derivatives, certified by ASTM International, can be blended only up to 50%. Yet, due to their resemblance in heating value to conventional fossil fuels and drop-in capability, e-fuels might be blended at higher ratios or even replace conventional fuels entirely [12, 14, 15].

In the context of e-fuels, Life Cycle Analysis (LCA) is used to infer the environmental impact of producing, using, and disposing of e-fuels as compared to conventional fossil fuels. Zang et al. [16] evaluated the well-to-wheel (WTW) greenhouse gas emissions from Fischer-Tropsch fuels throughout their full lifespan, concluding that WTW in the integrated system greenhouse gas emissions are 57-65% lower compared to traditional petroleum fuels [16]. Further LCA carried out by Bicer and Dincer [17] into kerosene and alternative fuels such as ammonia, methanol, ethanol, liquified natural gas, and hydrogen indicate ammonia, jet fuel, and methanol as the least expensive, with liquefied methane and hydrogen lead to less greenhouse gas emissions. On the other hand, Ballal et al. [15] looks into different scenarios including CO_2 source, H_2 generation, and electrolyzer efficiency, concluding considerable climate change mitigation is achievable until 2050, depending on the policies implemented in the electricity sector balanced against its production cost [18].

The present study aims to assess the feasibility of introducing e-fuels, in particular e-kerosene, into the global airline industry as a means of achieving carbon neutrality goals. The fleet system dynamics model (FSDM) [19] is employed to forecast commercial aviation emissions until 2100 for five different scenarios, considering an e-fuel blend ratio of 50% until 2050 progressively increasing up to 2100.

2. Air Transport System Modeling

Emission projections up to 2100 are obtained for the global airline fleet through the fleet system dynamics model (FSDM) [19]. It allows for evaluating air transport capacity and air traffic market data from information relative to fleet size, composition, and age distribution. The air transport ecosystem is modeled as operating on a network of air routes, defined by their number, length, and geographical position. In this context, FSDM takes a macro approach by considering the entire network of an airline (Figure 2). During each simulation year, the model requires information on Revenue Passenger Kilometers (RPKs) and Revenue Ton Kilometers (RTKs) to determine the capacity gap. This data is crucial for calculating the number of new aircraft that should be added to the fleet. Secondly, for model initialization, the user is required to specify the start year of the simulation, provide details about the initial fleet, and define the initial transport performance expected from the fleet. By embracing these principles, FSDM ensures a comprehensive and strategic perspective on fleet planning within the airline industry simulation.

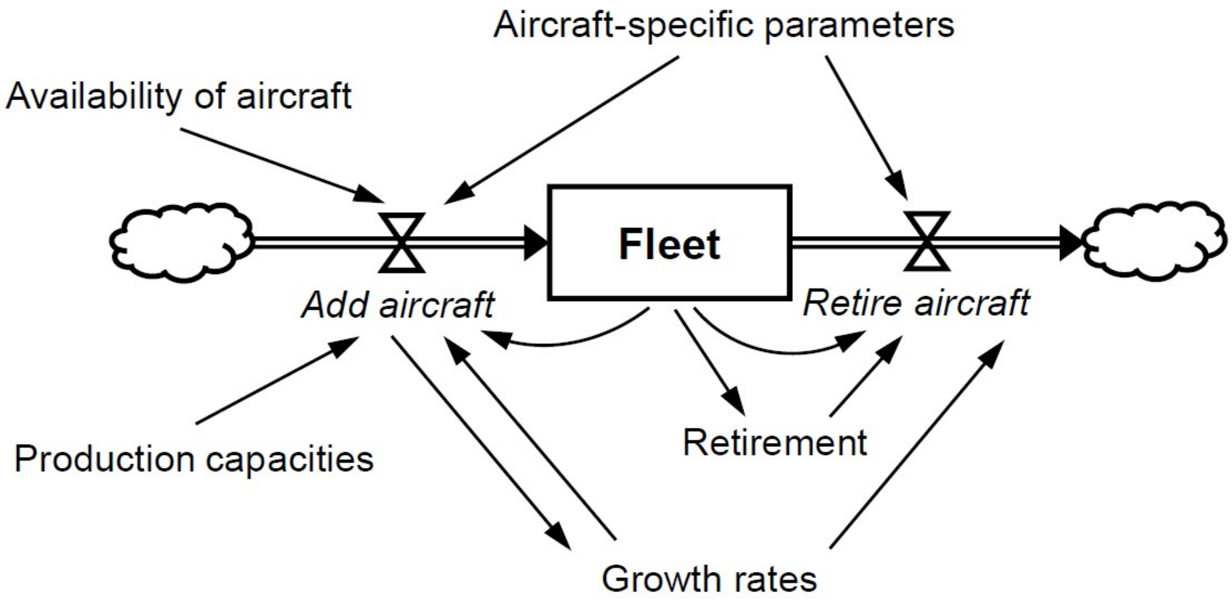


Figure 2 – Functional scheme of the FSDM based in System Dynamics [19].

Due to the high degree of complexity of the system, FSDM depends on important assumptions to simplify the modeling efforts:

- **Airline competition:** No airline competition is considered; instead global air transport demands are met by a single airline.
- **Fleet allocation:** The fleet fuel consumption is minimized as the fleet assignment problem's objective.
- **Simulation periods:** The minimum time interval is one year starting from 2008.
- **Representation of the global air transport fleet:** Specific aircraft categories, representative of the global fleet are created, replicating a given aircraft type.
- **Representation of the global routes network:** Air routes are defined following the Official Airline Guide (OAG) database [20]. These are simplified considering six global regions: Europe, North America, Latin America, Africa, the Middle East, and Asia.

3. Scenario Forecast

Emissions scenarios have been crucial for the Intergovernmental Panel on Climate Change (IPCC). In its most recent report [21], a novel approach, labeled as the Shared Socioeconomic Pathways (SSPs), was introduced [22].

Shared Socioeconomic Pathways (SSPs) constitute a pivotal element within a novel scenario framework established by the climate change research community. This framework aims to facilitate a comprehensive exploration of future climate effects, vulnerabilities, adaptation, and mitigation strategies [23]. As outlined by [22], SSPs delineate credible alternative trends in the development of society and natural systems, both globally and within significant world regions. Unlike other global scenarios, SSPs deliberately do not assume climate change, impacts, or policies; this deliberate omission serves a methodological purpose.

While climate change scenarios find broad applications in decision-making contexts, they often center on choices for addressing climate change through mitigation or adaptation. In contrast, SSPs focus on specific combinations of socioeconomic challenges related to mitigation and adaptation, as illustrated in Figure 3 [24].

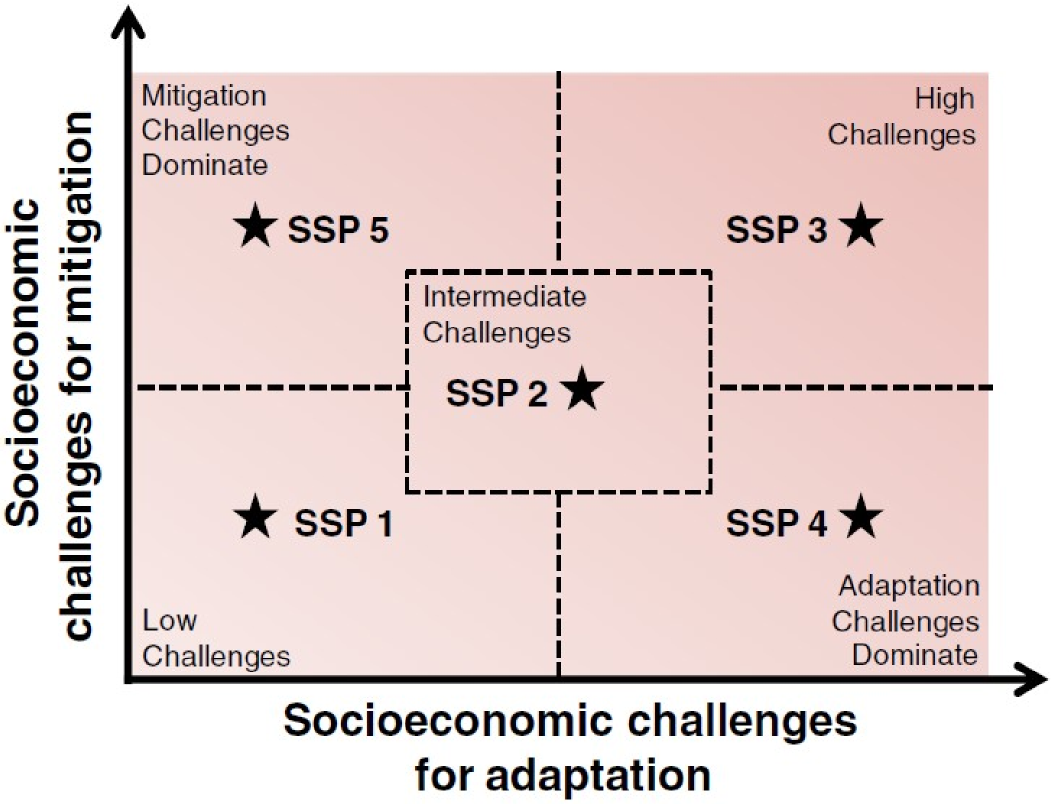


Figure 3 – Representation of the SSPs according to their combinations of socioeconomic challenges to mitigation and adaptation. [22].

The current collection of SSP scenarios comprises a series of baselines projecting future developments without additional climate policies beyond the existing ones. This collection also includes mitigation scenarios exploring the impacts of climate change mitigation policies [23]. The formulation of these narratives was influenced by three primary factors: gaining insights into societal development within the context of climate change scenarios, drawing on past experiences, and acknowledging the distinctive role of SSPs in delineating societal futures marked by unique combinations of challenges related to mitigation and adaptation [24].

Figure 3 illustrates the development of five narratives, where SSP1, SSP3, SSP4, and SSP5 describe various arrangements of challenges to adaptation and mitigation, while SSP2 represents a central case. SSP2 follows a development path consistent with historical patterns over the past century [24].

As mentioned, e-fuels have the potential to replace jet fuel in the future, but, for now, they can only be blended up to 50%. To see if, with the e-kerosene introduction, is possible to reach net-zero by 2050, 5 possible scenarios were created. These scenarios will depend on the blend ratio of e-kerosene with jet fuel, which will vary over the years:

- **Scenario 1**: In this scenario, the blend ratio is 50% until 2100;
- **Scenario 2**: In this scenario, the blend ratio is 50% until 2050, increasing 10% in the following decades, i.e., 60% in 2051-2060, 70% in 2061-2070, 80% in 2071-2080, 90% in 2081-2090, and 100% in 2091-2100;

- **Scenario 3**: In this scenario, the blend ratio is 50% until 2050, increasing 10% every next 5 years, i.e., 60% in 2051-2055, 70% in 2056-2060, 80% in 2061-2065, 90% in 2065-2070, and 100% in 2071-2100;
- **Scenario 4**: In this scenario, the blend ratio is 50% until 2050, 75% in 2051-2060, and 100% in 2061-2100;
- **Scenario 5**: In this scenario, the blend ratio is 50% until 2035, 75% in 2036-2050, and 100% in 2051-2100.

4. Emissions Calculation

The environmental impact analysis of e-kerosene, in terms of CO_2 emissions, is based on the Environmental Report by ICAO [25] that uses the quantity of SAF available and the respective life cycle to analyze the influence of SAF introduction in the emissions. Figure 4 depicts a flowchart of the calculation procedure, where CO_2 emissions(t) represents the total CO_2 emissions of the specific year, Jet fuel(t) the quantity of conventional jet fuel in kilograms of the specific year, E-kerosene(t) the quantity of e-kerosene in kilograms of the specific year, $\text{LCA}_{\text{E-kerosene}}$ the life cycle of e-kerosene (9.23 gCO_2e/MJ [26]), $\text{LCA}_{\text{Jet fuel}}$ the life cycle of conventional jet fuel (89 gCO_2e/MJ) and t the simulation year.

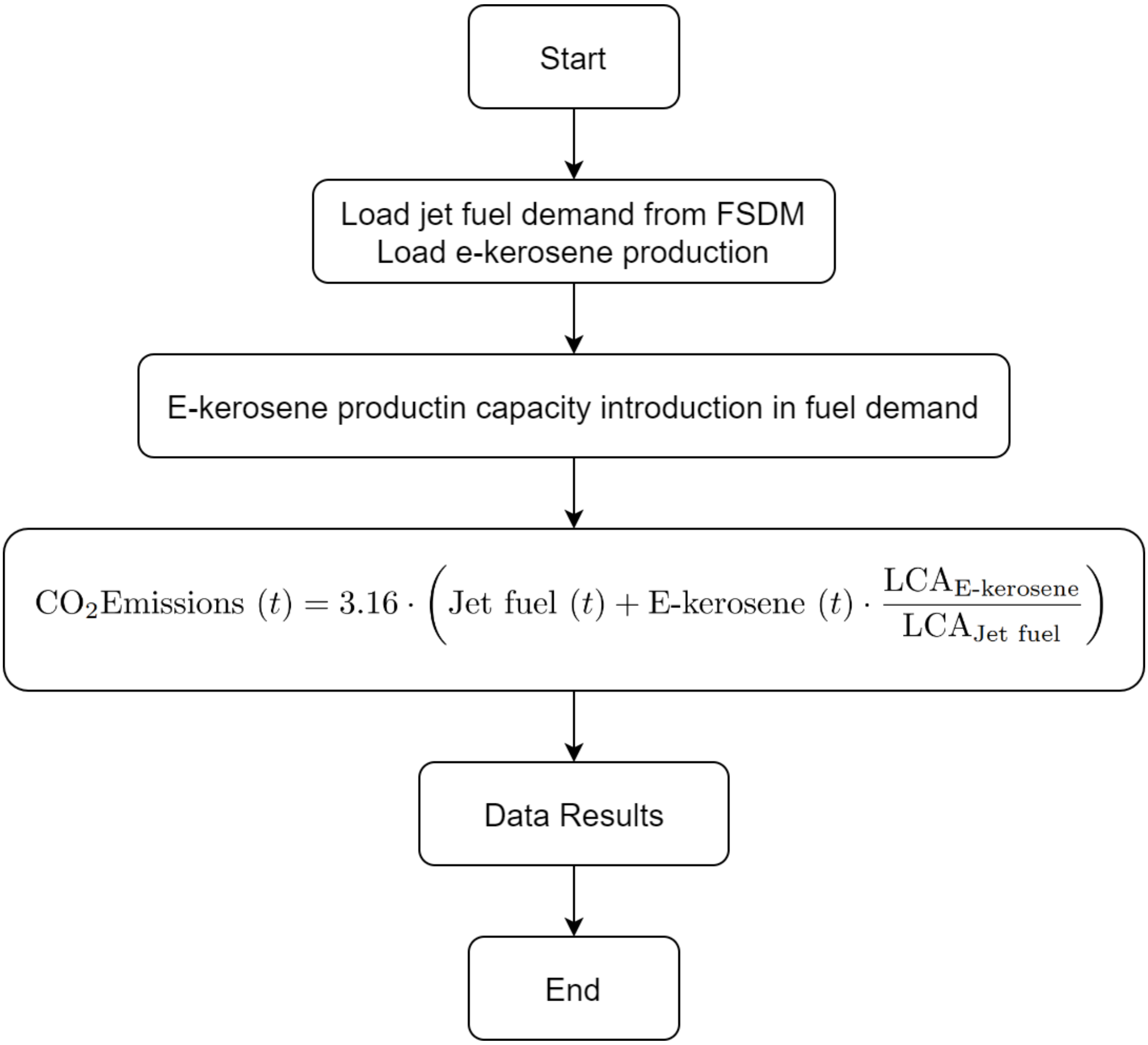


Figure 4 – E-kerosene emissions methodology

The first part of the methodology is to load the demand of jet fuel obtained with FSDM and load the production capacity of e-kerosene corresponding to each production rate case. Next, e-kerosene is introduced into aviation fuel demand, according to the required blend ratio. Lastly, chCO2 emissions are calculated, resulting from jet fuel and e-kerosene consumption.

Finding the world production of e-kerosene was challenging since it is a recent technology. Ongoing projects are presented in Table 1. Most of them have not yet started e-kerosene production, being projections made by the companies in charge. Starting in 2022, companies only project their production capacity until 2050. These projections are extended up to 2100 considering three cases in conjunction with the scenarios defined previously.

- Case A: 5% annual production rate from 2051 to 2100.
- Case B: 10% annual production rate from 2042 to 2100.
- Case C: 15% annual production rate from 2040 to 2100.

Table 1 – Projects and production capacity of e-kerosene.

Project name	Companies	Location	Start date	Production Capacity
Arcadia eFuels	Arcadia eFuels, Topsoe, Sasol, Technip Energies	Copenhagen, Denmark	2025	75000 tpa [27, 28]
Bilbao Decarbonization Hub	Petronor, Repsol, Aramco	Bilbao, Spain	2025	8000 lpd^a [29]
CAC Synfuel Plant	CAC Engineering	Chemnitz, Germany	2030	1 million lpa^b [27, 30]
INERATEC Pioneer Plant	INERATEC	Frankfurt, Germany	2024	2500 tpa [31]
Nordic Electrofuel - Plant 1	Nordic Electrofuel AS	Lysaker, Norway	2025	4.4 million lpa, 10.5 million lpa by 2026, 1 billion lpa by 2032, and 60 billion lpa by 2050 [27, 32]
Alpha Plant	Norsk e-Fuel, Sunfire, Norwegian, Carbon Centric	Vefsn, Norway	2026	50 million lpa, in 2030 will have a production capacity of 250 million lpa with 2 more production plants
ReuZe Project	Infinium, Engie	Dunkirk, France	2026	100000 tpa [27, 33]
DAWN	Synhelion	Julich, Germany, and Spain	2024	a few thousand lpa in Germany, 1.25 million lpa in Spain by 2026, 875 million lpa worldwide by 2030, 50 billion lpa by 2050 [34]

Acronyms: ^{a} lpd: litres per day; ^{b} lpa: litres per annum

5. Results

5.1 Baseline Definition

Projecting aviation emissions in aviation until 2100 is a challenging task due to the lack of available information. In this regard, SSPs offer valuable insights into air travel demand (RPKs) and their subsequent implications for fuel consumption. Franz et al. [35] forecasted global aviation demand until the year 2100 for SSP1, SSP2, and SSP5, including COVID–19 impact. However, it only includes global aviation demand and not demand by route.

A commercial market outlook (CMO) provided by Boeing reporting annual growth of RPKs, in percentage, until 2042 was used to establish a baseline for the CO_2 emissions and extrapolated to 2100. These results are depicted in Figure 5, corresponding to "Iteration 1".

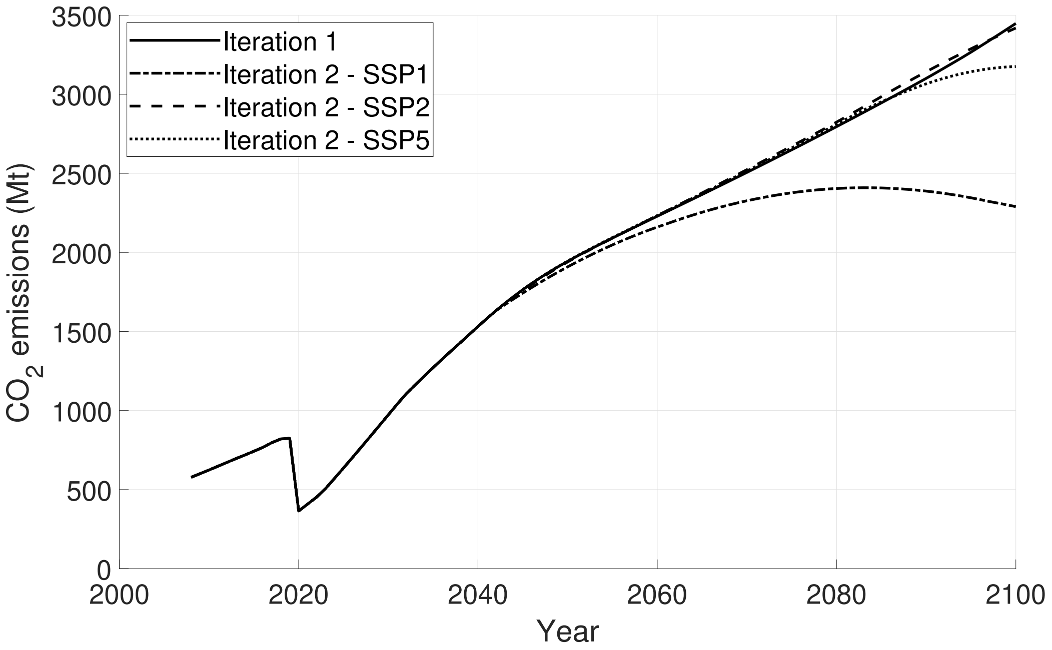


Figure 5 – CO_2 emissions prediction until 2100 for Iterations 1 and 2.

The influence of the different SSPs is also included in Figure 5, considering CMO values up to 2042, due to data availability. After this point, the RPK growth corresponding to each SSP is used. These are labeled "Iteration 2" for SSP1, SSP2, and SSP5.
A comparative analysis is then carried out with Grewe et al. [36] and ATAG's predictions [8]. Since ATAG's forecast extends only to 2050, linear and logarithmic data extrapolation was performed. Figure 6 only depicts the linear extrapolation due to the results being similar.

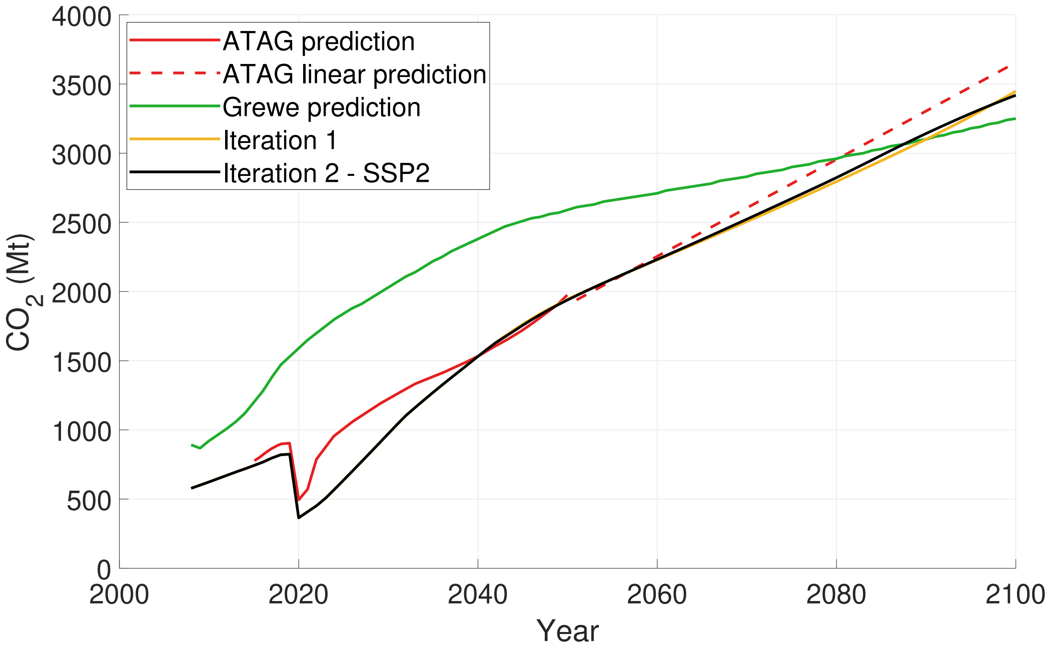
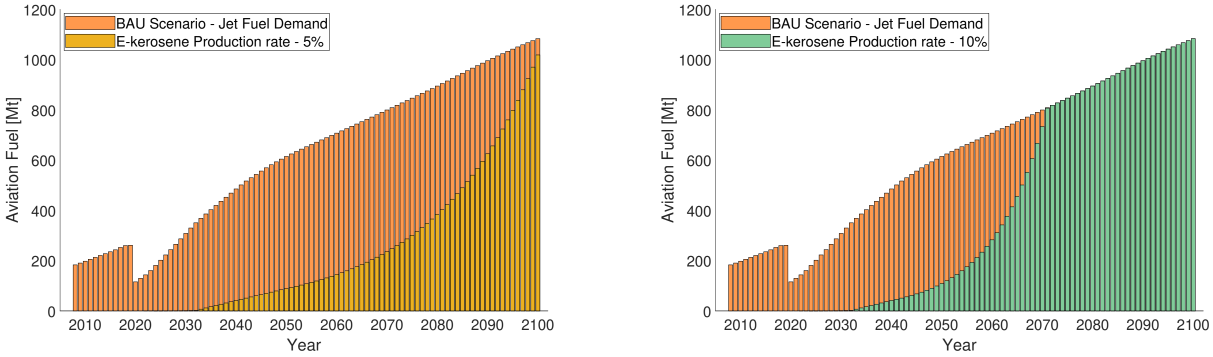


Figure 6 – Comparison with ATAG and Grewe et al. study.

Grewe et al. [36] projection is also depicted in Figure 6 excluding the COVID–19 pandemic effects. Regardless it is possible to conclude that despite different initial conditions and growth rates or even the omission of major phenomena, all projections indicate a very steep growing trend of CO_2 emissions resulting from commercial air transportation. Given these results, "Iteration 2 - SSP2" is selected as the baseline against which the scenario forecast will be compared.

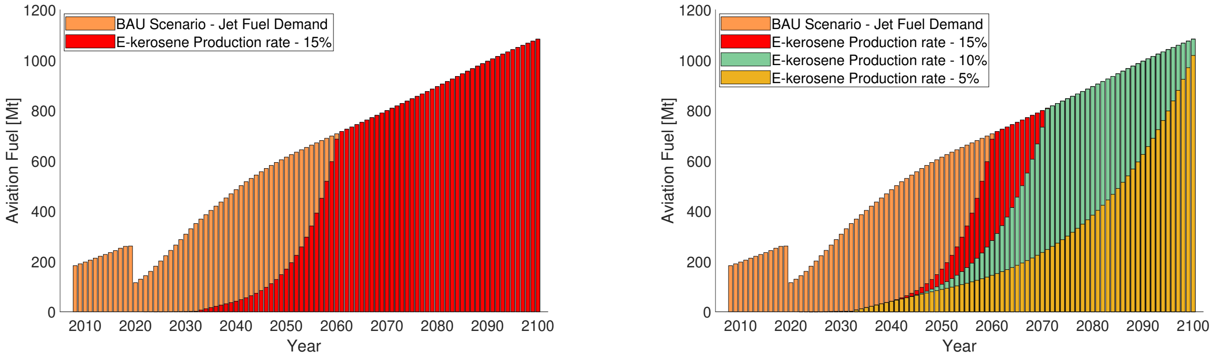
6. E-kerosene Impact

By analyzing e-kerosene production, Figure 7, is noticeable that in Case A, it never reaches jet fuel demand during the simulation time frame. On the other hand, in case B (production rate 10%) and case C (production rate 15%) demand is met in 2071 and 2061, respectively.
An important note is that e-kerosene production capacity has those annual production rates until it reaches the jet fuel demand, previously obtained with the FSDM model.



(a) Case A: E-kerosene production rate of 5%.

(b) Case B: E-kerosene production rate of 10%.

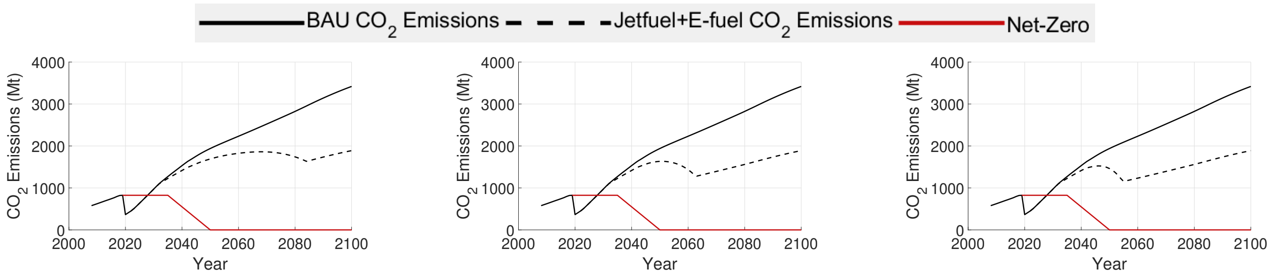


(c) Case C: E-kerosene production rate of 15%.

(d) Comparison with the 3 production rates.

Figure 7 – E-kerosene production and jet fuel demand.

In each projection, the three production capacity cases are studied and compared with the BAU scenario ("Iteration 2 - SSP2") and Net-zero CO_2 emissions.
In Scenario 1, it was considered a blend ratio with jet fuel of 50% until 2100. E-kerosene is an FT derivative, so, according to ASTM international, it can be blended up to 50%. Therefore, Scenario 1 is the most conservative. Figures 8a, 8b, and 8c depict the results for this scenario.



(a) Scenario 1 with a production rate of 5%.

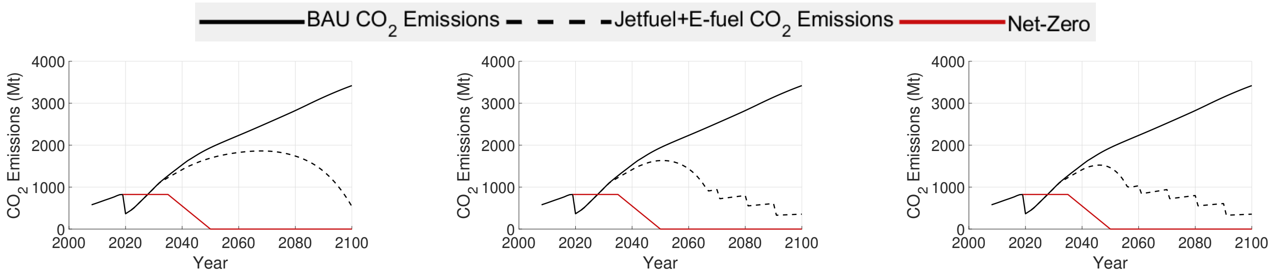
(b) Scenario 1 with a production rate of 10%.

(c) Scenario 1 with a production rate of 15%.

Figure 8 – Scenario 1.

For Case A, corresponding to Figure 8a, it is possible to notice a difference in CO_2 emissions starting around 2035, reaching carbon-neutral growth in 2067. This decrease persists until 2084, by which point, the production capacity is feasible to satisfy the demand, at a 50% blend ratio. In the last 16 years, CO_2 emissions start to increase again. This happens mainly because there is jet fuel in the mix. In the other 2 production rates, Figures 8b, and 8c, it is possible to see a faster decrease of CO_2 emissions, due to, bigger production rates. For a 10% production rate, carbon-neutral growth is achieved in 2050, and for a 15% it is reached in 2046. However, these e-kerosene production capacities, Case B and C, satisfy demand earlier, in which emissions start to increase in 2063 and 2055, respectively. With this blend ratio, for all cases in this scenario, the CO_2 emissions in 2100 are the same, corresponding to the value of 1889 Mt, never reaching net zero during the simulation time frame.

The next scenarios consider the possibility of using 100% e-kerosene, but they differ on when this condition is introduced. When the annual production of e-kerosene is 5%, the world aviation fuel demand is not satisfied as shown in Figure 9a. This also applies to Scenarios 3, 4, and 5 with a 5% production rate. For this Case, CO_2 emissions start to decrease around 2035, in comparison to BAU scenario (as it happens in Scenario 1). The carbon-neutral growth will be achieved in 2067, the same as the scenario before because it depends only on the production capacity.



(a) Scenario 2 with a production rate of 5%.

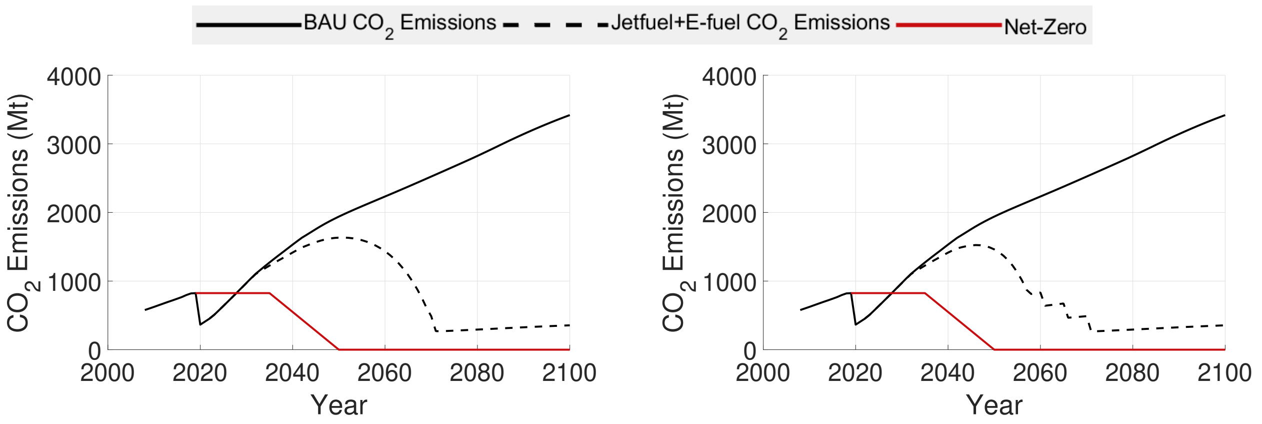
(b) Scenario 2 with a production rate of 10%.

(c) Scenario 2 with a production rate of 15%.

Figure 9 – Scenario 2.

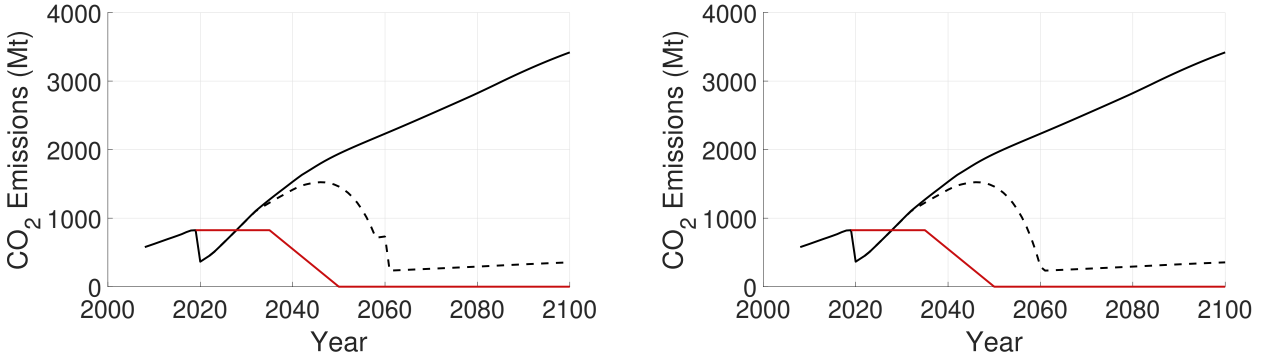
The first thing to notice in Scenario 2 (Figure 9) is that production capacity cases start to take on a staircase-like shape due to the new blend ratio limits that happen every decade from 2050. Each "level" corresponds to a percentage of e-kerosene in the fuel. For an annual production rate of 10%, the necessary amount of fuel to supply the global fleet is reached in 2067 with a blend ratio of 70% of e-kerosene with jet fuel. In the other case (Figure 9c), the fuel demand was satisfied earlier in 2057. Scenario 2 considers the use of only e-kerosene after 2090, in which the CO_2 emissions will never reach 0 Mt due to LCA values.

All results from Scenarios 3, 4, and 5 are very similar. However, in Scenario 5, the necessary fuel target is reached later in comparison to Scenarios 3 and 4. This occurs due to an earlier 100% e-kerosene blend ratio (in 2050). For a 10% production rate, Figure 10a, the forecast is equal for the last three scenarios, surpassing carbon-neutral growth in 2050. The lowest value of CO_2 emissions, 268 Mt, takes place in 2062 and starts to increase smoothly until 2100 as in Scenario 2, almost reaching half the emissions from 2005.



(a) Scenario 3 with a production rate of 10%.

(b) Scenario 3 with a production rate of 15%.



(c) Scenario 4 with a production rate of 15%.

(d) Scenario 5 with a production rate of 15%.

Figure 10 – Scenarios 3, 4 and 5

7. Conclusions

This study shows the potential of e-kerosene in reducing CO_2 emissions in aviation. Two methodologies were applied: the FSDM to simulate the world fleet and obtain the fuel demand until 2100 and LCA to account for the e-kerosene production process.

Results indicate that to reach carbon-neutral growth, the focus should be on the production capacity. The bigger the production rate, the earlier carbon-neutral growth will be reached. Another aspect is the importance the blend ratio has on CO_2 emissions. When the quantity of e-kerosene in the fuel mix increases, emissions will decrease.

The domain investigated in this study holds paramount significance for aeronautical entities and industry representatives. Its value lies in assessing the comprehensive reduction in CO2 emissions facilitated by the introduction of e-fuels in civil aviation. Future research endeavors must focus on evaluating if e-fuels are economically feasible in the future, but also on analyzing the role of new technologies, air traffic management, and operational strategies in curbing international aviation-related CO_2 emissions.

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