DOI: 10.13009/EUCASS2023-952
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

Techno-economic Analysis of Sustainable Aviation Fuels – E-fuel

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Abstract

The aviation industry is under increasing pressure to reduce its overall carbon footprint. However, it is expected that commercial air traffic will continue to expand at the same steady rate as it did before to the COVID-19 pandemic. Alternative fuels are therefore crucial for achieving future emission goals and reducing reliance on fossil fuels. The present study examines the feasibility of implementing Sustainable Aviation Fuels, including synthetic aviation fuels commonly known as E-fuels, to mitigate CO_2 emissions. Consequently, this study compares the results of life cycle analyses for different feedstock types and conversions using the GREET model as a database. The study concludes that forestry residues processed via the Fischer-Tropsch method exhibit the lowest emissions, while corn converted to ethanol for jet fuel shows the highest emissions. However, additional criteria should be considered to determine the feedstock with the lowest environmental impact.

1. Introduction

Sustained global efforts are required to combat climate change and reduce greenhouse gas (GHG) emissions, limiting their impact on humankind's quality of life and the environment. The transportation industry, in particular air transport, continues to rely heavily on carbon-based fuels, being responsible for 2.4% of CO_2 global emissions. Moreover, commercial aircraft traffic is expected to continue its growth trend exhibited up to the COVID-19 pandemic [1] as depicted in Figure 1. However, alternatives are required to meet the global market needs, while ensuring net zero emission scenarios.

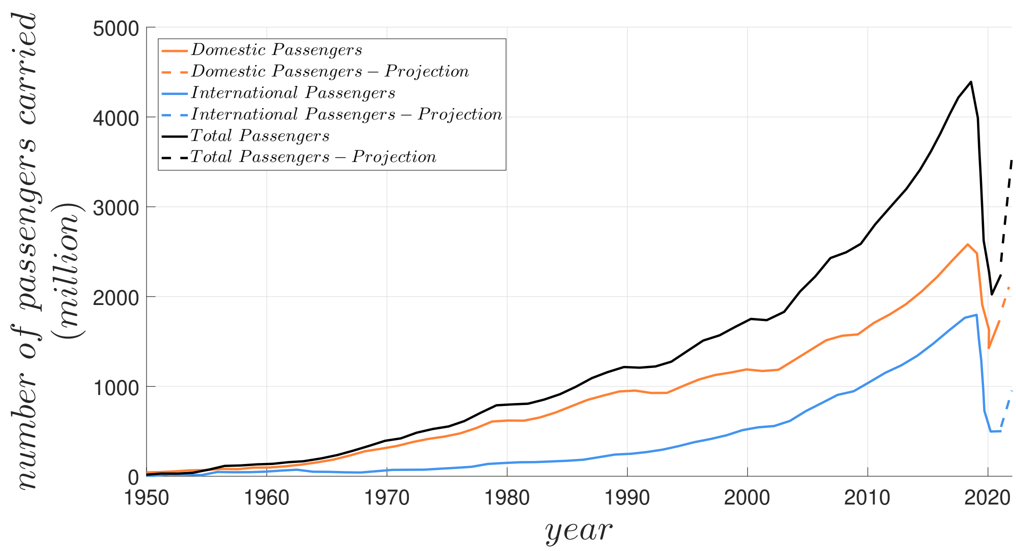

Figure 1: Global passengers carried until 2022 projections (adapted from Cabrera and de Sousa [1]).

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The Net Zero Scenario is an ambitious scenario that aims to achieve net zero CO_2 emissions by the year 2050. This is accomplished by strict climate laws and targets, which together limit global warming to 1.5 °C. According to the International Energy Agency (IEA), global CO_2 emissions from the aviation sector experienced a rebound in 2021, increasing by 7.8% to nearly 7.5 Gt CO_2 in 2021, up from 6.96 Gt CO_2 in 2020. When COVID-19 pandemic restrictions were lifted, traffic began to increase again after a historic decline in 2020 (Figure 1). The Net Zero Scenario claims a 20% reduction in aviation sector emissions to less than 6 Gt by 2030. The commercialization and expansion of low-carbon fuels, primarily in the aviation sector, as well as modal shift policies in favor compared with fewer carbon-intensive transport methods, would be necessary in order to achieve this reduction by the year 2030. According to Cabrera and de Sousa [1], the implementation of alternative fuels is fundamental to meeting future emission targets, while decreasing dependency on fossil fuels. In this sense, sustainable aviation fuels (SAFs) arise as a possible pathway, which includes biofuels and synthetic fuels (E-fuels). Additionally, the possibility of using hydrogen, in the long run, is also being considered [2].

The aviation industry [1], is in an urgent position regarding climate change. In order to reach the goals that have been set, the dependence of commercial aviation on fossil fuels must be reduced as much as possible and finally removed. The 27th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP27) [3] resulted in a package of accords in which nations reaffirmed their commitment to limit the rise in global temperature 1.5 °C above pre-industrial levels. In addition, the package improved efforts by governments to reduce emissions of greenhouse gases and adapt to the unavoidable effects of climate change. It also increased financial, technological, and capacity-building assistance to countries that are still in the process of developing their economies. The International Air Transport Association's (IATA) official resolution, which mandates that all of its member airlines achieve carbon neutrality by the year 2050, is shown in Figure 2. Predictions of CO_2 emissions without any further efforts until the year 2050, in comparison to the scenario in which there is no net increase in efficiency and the trend from 1990. To bring down emissions, we need to make some technological leaps (T), make some improvements to our operations and our infrastructure (O), switch to more environmentally friendly aviation fuels (F), and look at many additional carbon mitigation options (M).

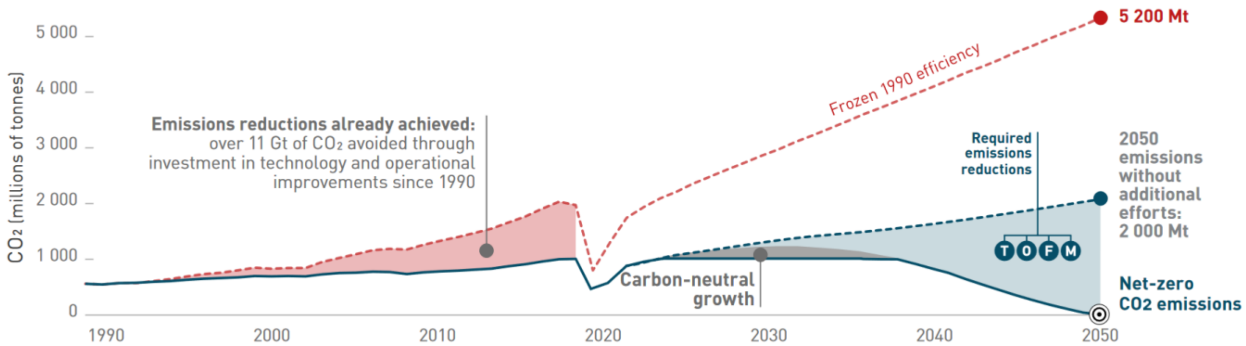

Figure 2: Prediction of Net-zero CO2 emissions until 2050 [1]

According to Timperley [4], there are several areas of focus that currently have potential in different ways. The emissions of greenhouse gases might be reduced by these sectors. For instance, enhancing planned maintenance and other operational procedures, and choosing aircraft paths that maximize emissions reductions rather than cost savings. Hydrogen- and battery-powered aircraft [1], are feasible alternatives if technological restrictions can be addressed in the future. Although these approaches would require considerable changes to aircraft design [5], the short-term implementation costs would be prohibitive for businesses. Therefore, it is only natural to examine these technologies as possible future solutions. Given that a wide range of feedstocks and production processes for sustainable aviation fuels are now approved for commercial use up to specific mix levels, drop-in replacements for conventional jet kerosene seem to have the potential for the short and medium term. Currently, biogenic materials account for most feedstocks. Nonetheless, sustainability is a barrier that must be solved before larger-scale applications can be adopted; as a result, power-to-liquids (PTL) systems would be worth considering. Despite the potential offered, research is still in the early stages [6].

Due to the significant growth of carbon emissions into the atmosphere, urgent action needs to be taken to reduce them. It is clear that the use of sustainable fuels will be one of the biggest contributions to achieving this goal. It is considered to be a solution not only in the long term but also in the short term. With the introduction of these fuels in aviation, it is necessary to make the required adaptations. Before that, it is necessary to study and better understand their environmental impacts. The main objective of this study is to understand the current state of sustainable fuels and how they compare to carbon-based fuels. A life-cycle (LCA) and techno-economic (TEA) analysis is carried out to assess

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the real environmental impact of using such fuels and what feedstocks would be better suited for their implementation.

2. Methodology

The aviation industry is one of the most difficult to decarbonize since it continues to be dependent on oil-delivered jet fuel despite efforts to find alternate options [7]. Due to the limited options for decarbonization, it is crucial to use sustainable aviation fuel effectively in order to help reduce greenhouse gas emissions. SAFs can be exploited effectively in already existing fleets, which allows large expenses to be avoided. In this sense, they must have the same physical and chemical features as traditional jet fuels, such as high cold stability and adequate energy density, to meet the significant demand for energy that is present in long-range flights. Some examples consist of jet biofuels, hybrid propulsion systems, hydrogen energy, and E-fuels. Electrofuels, also known as E-fuels, are a kind of synthetic fuel that may be generated by mixing hydrogen (H_2) with either carbon dioxide (CO_2) or nitrogen (N_2). Indirect electrification can take the form of E-Fuel and hydrogen, both of which can be synthesized using electricity. Electrolysis and E-fuel synthesis are two examples of this type of indirect electrification, which can be used to meet energy demands that are currently assured through gaseous and liquid fuels. Direct electrification is a competitive alternative, but in order to implement it, the end-use must first be converted to electric applications.

Electrolysis is the process that generates hydrogen, whereas fossil fuels are responsible for emitting carbon dioxide [8]. E-fuels are produced using a chemical process that does not include the use of petroleum or liquids derived from oil. Despite this, they have comparable properties to gasoline or diesel, including a high energy density and the ability to burn easily. According to the research conducted by Brynolf et al. [9], it is possible to produce a variety of liquid and gaseous E-fuels. The key advantage of E-fuels is their compatibility with the great majority of existing vehicles and systems. In addition, unlike fossil fuels, these synthetic fuels may be generated with net-zero emissions if only renewable energy, electrolysis-derived H_2, and CO_2 capture are employed. Low electricity-to-energy conversion efficiency and high production costs are the key disadvantages. Through the reduction of GHG emissions, the transportation sector contributes greatly towards climate goals. Currently, it accounts for around 24% of all fossil fuel-related CO_2 emissions worldwide. In addition, there is room to improve hydrogen production from energy, storage, and distribution, while promoting the stability of intermittent power sources. However, issues with storage, transmission, and distribution must be resolved before a technically viable hydrogen economy can be created. The current jet fuel distribution system, which uses pipelines, trains, trucks, and other modes of transportation to transfer fuel from refineries needs to be improved so that long-distance fuel transportation costs may be reduced are more reasonably priced feedstock accessed. Liquid E-fuels offer an advantage over other types of E-fuels. They are compatible with the current transportation and fuel distribution infrastructure and are simple to mix with conventional jet fuel (CJF). In addition, compared to gaseous fuels, their high energy density reduces the effect on vehicle capacity, volume, and weight. However, producing e-gasoline and e-diesel is difficult, costly, and requires a significant amount of renewable energy. A distinct distribution and replenishment mechanism would be necessary for e-fuels that contain oxygen. Due to their higher volume, mass, and higher pressure, gaseous fuels are more difficult to handle and store aboard vehicles. Gaseous fuel distribution is made more difficult by the additional equipment needed for distributing, compressing, and dispensing them [9].

The costs, in addition to the material needs, energy consumption, and environmental pollutants, differ from one technology to the next. These factors, in turn, have an effect on the findings of environmental evaluations of, for instance, the many routes that electronic fuel may be produced. The environment may be negatively impacted in a variety of ways by various materials, such as by varying degrees of GHG emissions caused by the use of power or the mining of metals.

In addition to costs, it is essential to take into account an LCA of the processes involved in the production of the SAF supply chain value. The International Civil Aviation Organization - ICAO [10] identifies the following as the two primary components that make up the life cycle emissions:

- Core Life Cycle Assessment (LCA) emissions - include all of the many steps involved in producing fuel, such as growing the feedstock, gathering it, recovering it, processing it, moving it, turning it into gasoline, distributing it, and burning it in aircraft engines. These emissions are analyzed to determine their effect on the environment.

- Emissions Caused by Induced Land Use Change (ILUC) - are taken into account by the Chemical Offsetting and Reduction Scheme for International Aviation (CORSIA). Due to changes in land use, the production of qualifying fuel may need more land usage, resulting in GHG emissions. This includes direct land use changes in the producing region as well as indirect changes in nearby areas that have an impact on biomass storage, soil organic carbon, and vegetation conversion. To take these effects into account, ILUC emissions are evaluated.

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When doing an LCA and TEA of Sustainable Aviation Fuels, there are several rules and factors to take into account. In terms of LCA, they are:

- Feedstocks: The type of feedstock used to produce SAF can influence how environmentally friendly the fuel is. The availability, sustainability, and effect on land usage of feedstocks should all be considered.
- Production process: The effectiveness, energy use, and emissions of the SAF production process should be assessed. Evaluation of the energy and water needs, as well as the usage of chemical treatments and other inputs, are all included.
- Distribution: The environmental effect of SAF distribution and transportation, including emissions from infrastructure building and transportation, should be assessed.
- End use: Based on their employment in aviation engines, SAFs' potential environmental effects, including combustion-related pollutants and any potential effects on engine performance, should also be assessed.

In terms of TEA:

- Costs: The fuel's economic viability should be assessed considering the capital and operational expenses related to its production. This involves calculating the costs of raw materials, machinery used for processing, labor, and energy.
- Market price: It is important to compare the market price of SAFs to the cost of conventional jet fuel. This entails assessing the need for SAFs as well as the accessibility and cost of replacing fuels.
- Policies and incentives: Government initiatives like regulations and tax reductions can have a big influence on how economically viable SAFs are. When analyzing the costs of manufacturing and the possible market for SAFs, they should be taken into consideration.
- Infrastructure development: It is important to assess how the expansion of infrastructure, such as manufacturing facilities and transportation networks, would affect the price of SAF production and distribution.

According to IATA, on March 17th, the base jet fuel price was 242.66 United States cents per gallon (cts/gal) equivalent to 0.6€/L. Table 3 shows the jet fuel price in €/L around the world.

Table 1: Jet fuel prices by continent.

	Jet fuel Price (€/L)
Base Price	0.6
Asia and Oceania	0.57
Europe	0.58
Middle East and Africa	0.55
North America	0.63
Latin and Central America	0.62

As for the GHG emission values presented in other studies, an inventory of results was made to carry out a comparative analysis. Moreover, equivalent emissions values are given in gCO2/MJ. In Table 2, according to Abrantes et al. [11], the carbon emission reductions are listed by their respective scenarios and corresponding dates. This scenarios [11] represent an increment in production capacity in relation to scenario A, defining the baseline condition from where climate impact can be inferred. In scenario D - Starting in 2030 a 15% increase is considered every year until 2050.

Table 2: Carbon emissions values categorized by scenario [11]

Scenario	Carbon Emissions	Year
A	$> 1.71\%$	2030
B	$< 18\%$	2050
C	$< 24\%$	2050
D	$< 38.5\%$	2050

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Table3 highlights the fact that the sustainable fuel produced via HEFA shows a higher cost compared to conventional jet fuel and also, the higher emission value achieved with conventional jet fuel (CFJ). In terms of price, HEFA is almost 3 times higher but has lower emissions. Table 4 shows the maximum and minimum values obtained for both proposed cases.

Table 3: Carbon emissions and fuel price comparison [1]

Fuel	Cost	Carbon Emissions
via HEFA	1.42€/kg	1.05 kgCO2e
CFJ	0.56€/kg	1.71 kgCO2e
Results	lowest price	higher emissions

Table 4: Reductions obtained in both cases.

	2023 Recovery Case	2024 Recovery Case
Min. Reduction	4.4% in scenario 3	1.9% in scenario 3
Max. Reduction	22.5% in scenario 4	23.4% in scenario 4

It can be seen in Table 5 that despite the effects on the environment, fossil fuel is still the most affordable today.

Table 5: Life cycle costs comparison.

	Life Cycle Costs (€)
Fossil	2.36
bio_SMR	7.15
syn_SMR	5.91
syn_Pem	21.40
syn_SOEC	16.62

In Table 6, according to IEA [2], it can be seen the values of emissions corresponding to each process and fuel. Jet fuel is the one that presents higher emissions compared to SAF. Biogas presents the lowest emission, but it is fuel gas that presents a greater difference compared to base fuel. In terms of agricultural practices, carbon capture, and storage present a greater reduction in emissions.

Table 6: Life Cycle GHG emissions comparison.

	Life-cycle emissions (gCO2e/MJ)	Processes	Reductions between SAF and base fuel (Kmt)
Petroleum Jet Fuel	84.5	Normal	101
Base	70.4		
H_2 Electrolysis	-3.7	H_2	186
Wind Turbine and CHP	-11.5	Electricity	
Biogas	-15.9	Heat	324
Fuel Gas	-1.8	CCS	514
RNG	-7	Farming Practices	
CCS	-34		
Sustainable Farming and SOC Change	-18.1		
Precision Farming Yield Increase	-4.7		

Table 7 highlights the emission values obtained for various fuel productions. The reductions were lower again for the stand-alone supply chain compared to the integrated one, and the lowest reduction that was obtained was with the same fuel by Fischer-Tropsch.

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Table 7: Life Cycle GHG emissions comparison categorized.

	GHG Emissions (gCO2e/MJ)
FT Diesel	100.3
Gasoline BOB from petroleum	92.8
Diesel from petroleum	91.1
Gasoline E10 from petroleum	90.2
Ethanol-corn grain dry milling (S-A)	52.5
Ethanol-nuclear LTE with H_2 recycled (I)	44
Ethanol-wind/solar LTE with H_2 recycled (I)	43.1
Ethanol-nuclear LTE without H_2 recycled (I)	41.9
Ethanol-wind/solar LTE without H_2 recycled (I)	40.8
FT-nuclear LTE with H_2 recycled (I)	38.5
FT-wind/solar LTE with H_2 recycled (I)	37.6
FT-nuclear LTE without H_2 recycled (I)	36.4
FT-wind/solar LTE without H_2 recycled (I)	35.3
FT-nuclear LTE with H_2 recycled (S-A)	8.6
Ethanol corn stover	11.4
FT-wind/solar LTE with H_2 recycled (S-A)	3.8
FT-nuclear LTE without H_2 recycled (S-A)	-2.7
FT-wind/solar LTE with H_2 recycled (S-A)	-8.3

3. Results

To perform the LCA of SAFs and E-fuels, the Greenhouse gases, Regulated Emissions, and Energy in Transportation (GREET) model, created by the Argonne National Laboratory (ANL) was used. The GREET model simulates emissions of conventional greenhouse gases (CO_2, CH_4, and N_2O) as well as the environmental pollutants from the fuels. The emissions of the three GHG are combined into a single carbon dioxide equivalent (CO2e) result using global warming potential (GWP) values. Carbon monoxide CO and volatile organic compounds (VOC) are both counted as CO_2 in their completely oxidized forms. The main sheets in the GREET workbook are a summary of the key input parameters for all fuel pathways, with input parameters that vary by target year, and calculate results providing provisions for a variety of fuels, vehicles, and feedstocks. Five conversion processes are considered in the present Study: Fischer-Tropsch (FT), hydrotreated vegetable oils (HVO), Synthesized IsoParaffin (SIP), Isobutanol Alcohol to Jet (ATJ) and Ethanol Alcohol to Jet (ETJ). Several types of feedstocks were considered for the different types of production.

Table 8, highlights the following:

- For production via Fischer-Tropsch
  - the lowest value obtained is forestry residues with 3.8 gCO2e/MJ
  - the highest value is corn stover with 10.73 gCO2e/MJ
- For production via HEFA
  - the lowest value obtained is used cooking oil with 11.88 gCO2e/MJ
  - the highest value is canola with 52.1 gCO2e/MJ
- For production via SIP
  - the lowest value obtained is sugarcane with 31.15 gCO2e/MJ
  - the highest value was sugarbeet with 38.29 gCO2e/MJ
- For production via ATJ
  - the lowest value obtained was sugarcane with 18.45 gCO2e/MJ
  - the highest value was corn with 56.02 gCO2e/MJ
- For production via ETJ

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- the lowest value obtained was sugarcane with 19.27 gCO2e/MJ
- the highest value was corn with 58.1 gCO2e/MJ

Sugarcane was the feedstock that, despite the various production methods, generates lower emissions. In general, the lowest value obtained was through forestry residues via FT and the highest value received was through corn via ETJ.

Table 8: Results obtained from GREET.

Conversion Process	Feedstock	LCA value (gCO2e/MJ)
FT	Corn Stover	10.73
	Forestry Residues	3.80
	Eucalyptus	7.68
	wheat Straw	6.95
	Willow	7.44
HEFA	Tallow	24.13
	Used Cooking Oil	11.88
	Palm Fatty Acid Distillate	27.28
	Corn Oil	16.33
	Soybean Oil	36.67
	Canola	52.1
	Camelina	41.64
	Palm Oil-Close Pond	32.50
	Palm Oil-Open Pond	52.50
	Brassica Carinata	34.60
SIP	Sugarcane	31.15
	Sugarbeet	38.29
ATJ	Sugarcane	18.45
	Miscanthus	40.34
	Forestry Residues	27.08
	Corn	56.02
	Corn Stover	31.74
	Molasses	23.02
ETJ	Sugarcane	19.27
	Corn	58.10

Figure 3 depicts a comparison between the results obtained by GREET, in orange, with those of Abrantes et al. [11], in blue. The steps considered in the obtained values were cultivation (depending on feedstock), harvesting/collection, transportation, conversion, distribution, and combustion. The variations represent the environmental impacts associated with the feedstock conversion used. The units used indicate the amount of GHG emissions measured in grams of carbon dioxide equivalent per unit of energy produced, megajoules. The challenge here is to determine which feedstocks or conversions are most environmentally friendly. An improved analysis would require evaluation criteria such as feedstock availability, land use, energy efficiency, or environmental impacts. Forestry residues via FT, which was the lowest result, there was a decrease in values compared to 2021, 8.3 gCO2e/MJ to 3.8 gCO2e/MJ. This suggests being potentially a more environmentally friendly feedstock. Regarding corn via ETJ, which can already be seen to be the highest result, there was also a decrease in values compared to 2021, 65.7 gCO2e/MJ to 58.1 gCO2e/MJ. As for the availability criteria, Forest Residues depend on all the forestry activities practiced, in which the consequent impacts can vary. Products like tallow are obtained from animal fat and are therefore not easy to obtain. Products like corn, sugar, oils derived from cultivated products, are products that can be produced in large quantities to avoid deforestation or the use of animals. As for the criteria for land use, we must be careful about the amount used. Deforestation, degradation, habitat loss, and crop loss are things to be considered. Therefore, products like oil are products that do not require land use because they are considered waste products. As for the energy efficiency criteria, it refers to the ratio of input and output energy required in conversions. Higher energy efficiency implies that less energy is wasted during the conversion, resulting in a more sustainable and environmentally friendly process. As for the criteria of the impacts that these may have on the environment, we must consider situations such as the effects on the ecosystem, the quality of water, air and land. Forestry residues may have the best impact regarding the reduction of emissions, but its

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use must be done in a sustainable way. Corn or any cultivated product, can lead to pollution due to excessive use of fertilizers and pesticides in cultivation. Despite the values obtained, it is always necessary to consider all these criteria.

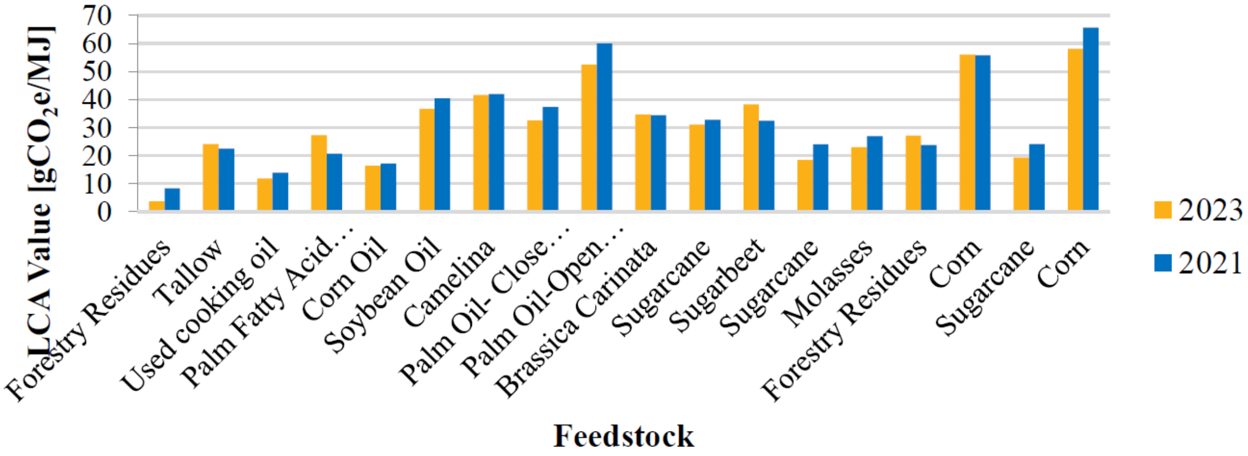

Figure 3: LCA values comparison.

Sustainable aviation fuels (SAFs) are fuels that can be used in aircraft engines as an alternative to conventional fossil fuels. They are created from renewable resources including biomass, waste, or solar energy. SAFs have the potential to decrease the aviation sector's carbon footprint and contribute to meeting global climate targets, arising in a variety of forms, including biofuels, synthetic fuels, and fuels based on hydrogen. Biofuels are made from organic materials like plants, algae, or waste. They can be used as a stand-alone fuel or combined with regular jet fuel. Chemical reactions transform carbon dioxide and hydrogen into liquid fuel to create synthetic fuels. Liquid hydrogen and ammonia, two fuels based on hydrogen, are made using renewable energy. SAFs provide a number of advantages over conventional fossil fuels. They generate less GHG and other pollutants, which decreases the environmental impacts of flying. As such, SAFs may contribute to humankind's energy security and decrease reliance on imported oil. Additionally, the development of SAFs has the potential to boost economic expansion and bring new employment to the renewable energy industry.

The outlook is not to switch in 5 years, and it is necessary for everyone to transition, whether to jet diesel or electric. Hydrogen technology is not something new, but its safety is still being questioned and needs to undergo further evolution as well. In aviation, one of the factors we always have to consider is the fuel loads we carry. Currently, the price of fuel is cheaper compared to hydrogen.

The outlook for hydrogen production is its environmental benefits, as it produces water vapor when burned, resulting in net zero emissions. This makes e-fuels a more viable option in the short term, as they can be used in existing engines. Future predictions suggest an increase in production to meet higher demand and lower costs, thanks to greater abundance. This would require investments in production infrastructure using renewable resources and the implementation of policies to encourage production. Additionally, establishing standards that meet specific environmental criteria is necessary to avoid negative impacts on land and resource utilization. Encouraging partnerships and collaborations are crucial to sustaining the implementation of e-fuels, including information campaigns and sharing best practices to expedite their development and adoption worldwide.

4. Conclusions

The extensive use of SAFs is accompanied by several issues, one of which is the high cost. This implies that significant effort and development will be required for SAFs to be widely adopted. For the year 2050, multiple regulations and goals related to SAFs have been established to create a more environmentally friendly and low-carbon aviation sector. These provisions include the following:

- Net-zero emissions: By 2050, the aviation sector aims to achieve net-zero emissions.
- Increase in SAF production: The International Air Transport Association (IATA) projects the generation and consumption of 2 million tonnes and 5 million tonnes of SAFs respectively by 2025 and 2030. Achieving exclusive use of SAFs by 2050 will require a substantial increase in availability and production.

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- Research and development (R&D): Industry investment in R&D aims to enhance the manufacturing process and reduce the price of SAFs. This involves exploring new feedstocks, conversion technologies, and improving production efficiency.

- Government support: Governments are encouraged to provide assistance in the creation and adoption of SAFs.

- Infrastructure development: The aviation sector needs to invest in facilities for the manufacturing, distribution, and storage of SAFs. This includes constructing new industrial facilities, upgrading existing infrastructure, and establishing new supply networks.

In conclusion, sustainable aviation fuels offer numerous opportunities to reduce the negative environmental impact of aviation and contribute to global climate goals. The lowest emissions were observed with forestry residues processed via FT, indicating their potential as a more environmentally friendly feedstock, subject to sustainable forestry practices. However, overcoming challenges in manufacturing and distribution will require significant investment and development. The aviation sector has made a commitment to reduce its environmental impact and support international climate change efforts, as reflected in these regulations and objectives. Governments, industry stakeholders, and the general public must collaborate and invest to achieve these goals. Life cycle analysis (LCA) and techno-economic analysis (TEA) are crucial techniques for assessing the sustainability and economic viability of SAFs. Making informed decisions regarding the production and adoption of SAFs will be crucial as the aviation sector strives to reduce its environmental impact and transition to a more sustainable future. The guidelines and considerations for conducting LCA and TEA of SAFs reflect the complex and diverse nature of sustainable aviation fuel development and use. By considering the environmental, economic, and social aspects of SAFs, decision-makers can make informed choices to promote their responsible production and utilization.

Acknowledgments

The present work was performed under the scope of activities at the Aeronautics and Astronautics Research Center (AEROG) and Institute of Mechanical Engineering (IDMEC) of the Laboratório Associado em Energia, Transportes e Aeronáutica (LAETA), and was supported by the Fundação para a Ciência e Tecnologia (Project Nos. UIDB / 50022 / 2020, UIDP / 50022 / 2020 and LA / P / 0079 / 2020).

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