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Assessing the Viability of Sustainable Aviation Fuel Decarbonisation: Environmental and Economic Sustainability

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Abstract:
The utilization of drop-in alternative fuels in airplanes has the potential to help the European aviation industry meet its sustainability objectives. These fuels can serve as a temporary solution in the short and medium term without requiring any structural adjustments to aircraft powertrains. However, the production process for alternative fuels is often energy-intensive, and some raw materials are linked to adverse environmental effects. Moreover, producing these alternative fuels tends to be more costly compared to fossil kerosene, which may hinder their attractiveness. Hence, this study examines the ecological and financial implications of four types of alternative fuels versus fossil kerosene from a well-to-wake perspective. The analyzed sustainable aviation fuel options include those derived from power-to-liquid and biomass-to-liquids pathways. Environmental impact assessment (life cycle assessment) and economic evaluation (life cycle costing) methods are employed in this analysis. The findings reveal that using sustainable aviation fuels can mitigate airplane operation's environmental impacts; however, significant reductions require an electricity mix based on renewable energies. Furthermore, economically speaking, conventional fossil kerosene remains preferable among the alternatives explored here according to both standard scenarios as well as scenario analyses conducted.

Keywords: sustainable aviation fuels, bio-derived kerosene, synthetic jet fuel, life cycle evaluation, cost analysis over product life cycle, assessment from production to use phase.

1. Introduction

The demand for both passenger and freight flights has significantly increased in recent decades. As a result of ongoing global integration and nearly limitless travel options, the worldwide aviation industry is projected to continue growing (ITF impact report 2018-20, n.d). Pre-pandemic research on the top two aviation companies, Airbus and Boeing, projected that there would be a potential annual increase in flight demand of around 4.5%, resulting in air traffic doubling every 16 years(Airbus, 2019., 2019). The COVID-19 pandemic caused a 75% decrease in air travel in 2020, leading to a temporary slowdown in growth. However, there has been a full recovery in the demand for flights, and a highly positive trend is anticipated for the long term(Gößling et al., 2021).

While this progress is favourable for the economy, it brings about significant adverse effects on the environment. The release of greenhouse gases, including carbon dioxide, has detrimental and enduring consequences on the climate as a result of heightened global warming (EASA, 2019). In 2019, the airline industry accounted for 2.6% of worldwide CO2 emissions and 5.9% of global human-caused greenhouse gas emissions. Despite potential fuel efficiency gains of around 25% per new generation of aircraft, the projected increase in air travel is set to triple aviation-related greenhouse gas emissions by 2050 (Gnadt et al., 2019). This is especially important because the effects of emissions at high altitudes are more serious than those from emissions at ground level (Jungbluth & Meili, 2018)(Lee et al., 2021).

The adverse effects stem primarily from the burning of fossil kerosene when operating the flight (Andruleit et al., 2018), which results in the emission of around 2.5 kg of CO2 per liter of kerosene. An average medium-range airplane, like the Airbus A320, uses approximately 2700 liters of kerosene per hour of flight and produces 6750 kilograms of CO2 emissions during this time (Shen et al., 2018).

Political measures have been implemented to mitigate the adverse effects on the environment and address growing societal concerns by reducing emissions. In the aviation industry, a range of strategies has been developed, including the implementation of initiatives like the "Carbon Offsetting and Reduction Scheme for International Aviation" (SARPs, 2021). The European aviation sector has set ambitious targets for 2050 under the Flightpath 2050 strategy. These goals include cutting CO2 emissions by 75% per passenger kilometer traveled (pkm), reducing nitrogen oxides emissions by 90% per pkm, and achieving a subjective noise reduction of 65% compared to new aircraft from the base year 2000 (Flight path - 2050, 2011). The first move towards reaching these reduction targets involves requiring airlines to participate in the European Union Emission Trading System for flights within Europe (Acare, 2018). CORSIA and the EU ETS primarily seek to offer monetary recompense for the environmental effects of air travel. Additionally, more wide-ranging strategic ideas in the aviation industry are crucial for advancing sustainable aviation without reliance on fossil fuels.

Although there is an expectation of ongoing advancements in aviation technologies, simply enhancing the efficiency of existing technologies will not be adequate to significantly reduce their harmful environmental effects (Kumar, N.; Möller, U, 2020). As a result, there will inevitably be disruptive technologies or radical changes to the powertrain system (Barke et al., 2021). The aviation sector is placing more attention on adopting alternative powertrain technologies in aircraft, such as fuel cell-based and battery-based concepts. These technological transitions entail significant structural modifications to the aircraft. However, their implementation in the near future faces challenges due to ongoing research and approval processes (Melo et al., 2020). Given the extended utilization periods and extensive research and development timelines ranging from 20 to 30 years for aircraft and powertrain concepts, it's essential to have short-to-medium-term solutions that align with the long-term transition (Melo et al., 2020).

One potential option is the utilization of drop-in compatible alternative fuels, which can be combusted in place of traditional fossil kerosene without necessitating any modifications to the aircraft's structure. While their combustion results in nearly identical CO2 emissions, notable reductions from a well-to-wake standpoint can be attained by realizing savings during production (Schmidt et al., 2018). Furthermore, alternative fuels do not contain sulfur or aromatic compounds, leading to reduced emissions of particulate matter and NOx during combustion. However, their manufacturing process is frequently energy-intensive, and certain feedstocks contribute to environmental pollution. Moreover, the production of alternative fuels is often more costly than that of fossil kerosene; this is a critical factor for airlines considering their usage (Chiaramonti et al., 2021). It is essential to thoroughly analyze and evaluate the potential contribution of these alternative fuels in achieving Europe's ambitious emission reduction targets.

This article aims to analyze and evaluate various alternative aviation fuels in terms of their potential to serve as a viable transition solution for the sustainable transformation of the European aviation industry. The production processes of four different alternative fuels - three based on power-to-liquid pathway and one based on biomass-to-liquid pathway - are modeled and examined for their use in aircraft engines. A comprehensive sustainability assessment is carried out, utilizing life cycle assessment and life cycle costing methods from well-to-wake perspective. Following this, the environmental and economic impacts of the alternative fuels are compared with those of fossil kerosene.

The rest of this article is organized as follows. In Section 2, promising aviation fuels are identified, their characteristics are explained, the assessment methods are outlined, and the system under investigation is defined. Section 3 presents and discusses the impact assessment results of the well-to-wake analysis. Different compositions of the electricity mix are considered to reflect the use of renewable energies in alternative fuel production. Section 4 discusses the implications of these results while Section 5 concludes with a summary outlining both benefits and limitations of this study and future research prospects.

2. Materials and Methods

2.1. Aviation Fuels and Previous Sustainability Studies

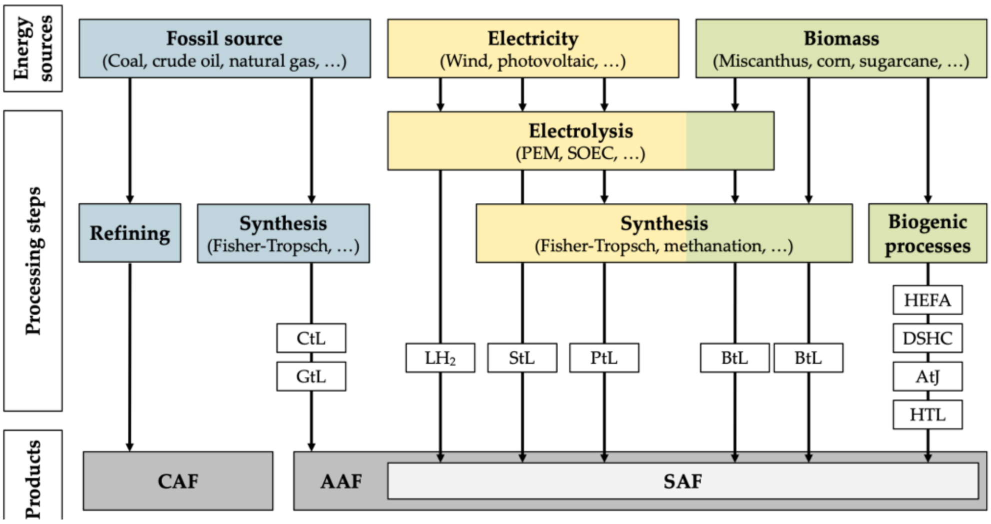
At the 2017 Aviation and Alternative Fuels Conference, new definitions related to turbine fuels and their production methods were introduced. These include conventional aviation fuel, aviation alternative fuel, and sustainable aviation fuel (SAF for aviation - ICAO, 2017). A schematic overview of the different types of aviation fuels is shown in **Figure 1.**

CAFs are aviation fuels produced exclusively from petroleum sources such as crude oil, liquid natural gas condensates, heavy oil, or oil sands through refinery processes. A common CAF variant is the traditional Jet-A1 fuel. In contrast to CAFs, AAFs originate from non-petroleum sources that can be either renewable or non-renewable including biomass, natural gas, electricity, or hydrogen. Fuels within AAFs derived from renewable sources are known as SAFs (Sustainable Alternative Jet Fuels, 2020). Initially, AAFs encompassed all options other than fossil kerosene. However, differentiation is now possible between drop-in fuels and non-drop-in fuels(Bauen et al., 2020). Drop-in fuels have the potential to be mixed with or even replace fossil kerosene without altering the existing powertrain setup, whereas non-drop-in fuels such as liquid hydrogen necessitate significant modifications to the powertrain. These structural alterations entail longer development periods and are costly. As a result, drop-in capable fuels are particularly seen as promising alternative aviation fuels for making short-term contributions to sustainable aviation efforts (Kramer et al., 2022).

Most of the drop-in AAFs are generated through pathways converting X into liquid (Liu & Yang, 2020), X represents the primary energy source. Possible energy sources include gas, coal, biomass, and hydrogen. Gas-to-liquid and coal-to-liquid processes are employed to create AAFs from non-renewable sources. On the other hand, potential pathways for producing alternative fuels from renewable sources involve biomass-to-liquid, power-to-liquid, and sun-to- liquid, which yield SAFs (Kramer et al., 2022). Various authorized production methods for the mentioned pathways are available, including Fisher-Tropsch synthesis, methanol synthesis, and methanation. FTS is the predominant industrial process with well-established commercial viability leading to economical operational expenses. The initial stage involves the reverse water gas shift reaction to generate synthesis gas from hydrogen, electricity, and CO2. This synthesis gas is then transformed into syncrude during FTS and subsequently refined into alternative fuel through hydrocracking and hydrogen addition (Kolosz et al., 2020). Prior to the synthesis processes, electrolysis is frequently employed to produce the necessary hydrogen. Furthermore, in terms of biomass, alternative production methods for SAFs exist apart from the BtL pathway. These include hydrothermal liquefaction, hydroprocessed esters and fatty acids, alcohol-to-jet, and direct sugar to hydrocarbons.

Nonetheless, the fuel production capacities using these techniques remain limited and are not addressed in this research (Shahabuddin et al., 2020).

Figure 1. Classification and production pathways of aviation fuels.



Numerous research has been conducted to analyze the adverse environmental effects of the aviation industry(e.g.,(Melo et al., 2020)(Chester & Horvath, 2009)(Cox et al., 2018)). The research primarily emphasizes that a significant portion of the adverse environmental effects of the airline industry are due to flight operations, specifically the burning of fossil kerosene. This accounts for approximately 77-91% (varies based on aircraft type and mission profile) of greenhouse gas emissions related to air travel (Chester & Horvath, 2009)(Cox et al., 2018). The rest of the greenhouse gas emissions come from other stages and can be linked to the production of aircraft, production of kerosene, transportation, and airport infrastructure.

Studies on alternative fuels, aimed at substituting fossil kerosene and projected to decrease greenhouse gas emissions through production savings, have seen a growing focus in recent times .(Melo et al., 2020),(Gutiérrez-Antonio et al., 2017),(Doliente et al., 2020) and (Doliente et al., 2020)Comprehensive descriptions of this area have been provided. Drop-in SAFs rely on biomass and are also known as biokerosene, garnering significant focus in current research(e.g.,(Schmidt et al., 2018),(Han et al., 2013),(Staples et al., 2018)). The studies mentioned above analyze the overall effects of substituting kerosene with biokerosene and its production using various feedstocks. Previous research indicates that potential feedstocks include lignocellulosic biomass (such as miscanthus), starch, sugar, vegetable oils, and fats (Schmidt et al., 2018). Various production methods can be used to further process them, such as FTS, HEFA, HTL, At], or DSHC (Schmidt et al., 2018).

By utilizing these BtL pathways, it is possible to achieve a reduction in greenhouse gas emissions of 63-89% from the well-to-wake perspective when compared to fossil kerosene(Han et al., 2013),(Staples et al., 2018). The extent of these decreases relies significantly on the electricity mix used in production. If biokerosene is manufactured using the current electricity mix, greenhouse gas emissions are around 2.4 times greater than those for fossil kerosene throughout its life cycle. Therefore, utilizing renewable energy-based electricity is a crucial means to lower climate-harming GHG emissions(Biçer & Dinçer, 2017). Scientific discussions also examine land utilization for growing first- and second-generation feedstocks, in addition to greenhouse gas emissions. It has become evident that second-generation feedstocks are particularly promising because they do not compete heavily with food crop cultivation. However, the emphasis should ultimately be on third-generation feedstocks(Hileman & Stratton, 2014). Studies with an economic emphasis primarily assess the competitiveness of biokerosene in comparison to fossil kerosene, and analyze its potential for market penetration.

The analysis suggests that biokerosene incurs notably higher costs of production, primarily due to increased energy requirements and subsequent elevated energy expenses. Further enhancements in the production methods are necessary to decrease energy consumption and enhance overall production efficiency (Doliente et al., 2020).

In addition to biokerosene, synthetic kerosene produced through the lt pathway is considered a potential solution for reducing environmental impact and transitioning the aviation industry from traditional to renewable fuel. This approach allows for leveraging existing aircraft systems and airport infrastructure. Synthetic kerosene generated via PL pathways has been shown to emit fewer greenhouse gases throughout its life cycle than fossil-based kerosene, while also consuming less land and water during production compared to biokerosene. However, its production remains challenging due to high energy requirements, necessitating a significant share of renewable energy in the electricity mix to mitigate environmental impacts. Similar to biokerosene, this high energy demand leads to higher production costs (Schmidt et al., 2018).

In addition to conventional drop-in fuels, numerous studies have been conducted on the sustainability implications of non-traditional drop-in fuels (e.g.(Koroneos et al., 2005)(Sürer & Arat, 2017). Liquid hydrogen, in particular, is highly valuable because of its benefits in reducing greenhouse gas emissions, acidification, summer smog, and eutrophication when compared to fossil kerosene. However, these advantages can only be realized if the electricity used for producing hydrogen comes from renewable sources - leading to higher production costs once again. Additionally, since hydrogen is not a direct replacement fuel (drop-in), it necessitates significant structural adjustments and extensive modifications to the aircraft powertrain (Bauen et al., 2020)

Prior research within the scientific realm primarily delves into examining the environmental implications linked with the production and utilization of biokerosene, often drawing comparisons with fossil kerosene to gauge their viability. However, economic considerations have been marginally addressed. Moreover, there's a dearth of studies pertaining to synthetic kerosene, and a thorough comparative evaluation encompassing fossil kerosene, biokerosene, and synthetic kerosene from a well-to-wake standpoint is notably absent in existing scientific literature. Such an investigation is imperative to assess alternative fuel potentials vis-à-vis fossil kerosene, taking into account both environmental and economic facets, pinpointing critical areas across the entire supply chain, and formulating recommendations for future research endeavors.

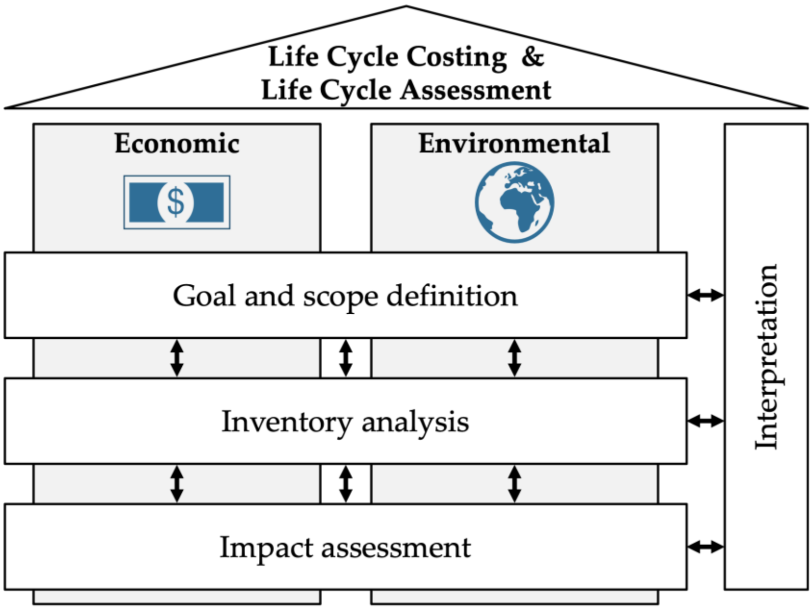
2.2. Assessment Method

Numerous approaches have been created to evaluate the environmental, financial, and societal consequences linked to products, operations, and supply chains. Widely used methods for measuring the environmental effects of a subject under study encompass life cycle assessment, carbon footprint analysis, cumulative energy demand evaluation, material flow analysis, and environmental impact assessment (Finkbeiner et al., 2010),(Ness et al., 2007). Besides the environmental evaluation techniques, there are various economic evaluation methods that can be used, including life cycle costing, techno-economic assessment, and the net present value method (Ness et al., 2007), (Zimmermann et al., 2020). Social impacts have grown in significance recently. Methods like social life cycle assessment, evaluating social sustainability, and analyzing human development are now utilized to measure the societal effects of a subject under scrutiny (Melo et al., 2020),(Ness et al., 2007).

This research investigates the environmental and economic impacts of kerosene and four SAFs from a well-to-wake standpoint. Social analysis is omitted as the study concentrates on a European supply chain setup where prevalent social risks in global supply chains, such as child labor, forced labor, or corruption, are minimal and conducting an insightful analysis would be impractical (Finkbeiner et al., 2010),(Guinée et al., 2010).

This study investigates the environmental and economic impacts of kerosene compared to four Sustainable Aviation Fuels (SAFs) from a well-to-wake perspective. Social analysis is omitted because the focus is on a European supply chain setup, where common social risks in global supply chains like child labor, forced labor, or corruption are minimal, making meaningful analysis challenging. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) are widely used in both scientific and industrial circles for quantitatively assessing the sustainability of products and processes. Therefore, they are also employed in this article's evaluation. The fundamental LCA and LCC procedure follows ISO 14040/14044 standards and is divided into four phases: (1) defining goals and scope, (2) inventory analysis, (3) impact assessment, and (4) interpretation, (Singh et al., 2012)(Keller et al., 2015). The schematic procedure is presented in

Figure 2. Methodology of life cycle assessment and life cycle costing.



Usually, LCA and LCC start by outlining the goals of the research and its extent. They define the subject under study within the system's boundaries and establish a functional unit as a basis for normalizing all energy and resource flows. Next, they gather inventory data describing exchanges between individual processes in the studied system and the external environment over its life cycle. Afterwards, they allocate this inventory data to impact categories for further assessment before calculating impact scores. The evaluation findings are then analyzed taking into account decision-makers' preferences to provide support for decision-making. This stage is closely connected with other stages and may be repeated when new perspectives, data constraints, or stakeholder opinions necessitate a redefinition of the study's focus, objectives, or methods (Singh et al., 2012),(Keller et al., 2015).

During the inventory analysis phase, documentation includes natural resources, emissions released, and land use. Subsequently, in the impact assessment stage, the results of the inventory analysis are linked to different areas of protection (human health, ecosystems, and resources). These endpoint indicators are determined based on midpoint indicators like climate change, mineral resource depletion, or formation of photochemical oxidants. Characterization factors are utilized to evaluate the influence of these midpoint indicators (Finnveden et al., 2009). LCC evaluates the economic elements of the system being analyzed. It is a cost-focused approach designed to calculate the expenses linked to a product or system, considering external factors that may be brought within in the future 581 One prevalent technique is environmental L.CC., which addresses the costs connected with a product or system within specified boundaries. The functional unit aligns with that used in LCA (Heijungs et al., 2012).

2.3. System Definition

This study seeks to examine the environmental and economic effects of medium-haul flight activities when using various Sustainable Aviation Fuels in comparison to traditional fossil kerosene. The assessment was carried out from a comprehensive perspective, encompassing the entire fuel supply chain and flight operations. This includes unit processes related to feedstock production, electricity generation, fuel distribution and storage, as well as fuel combustion in aircraft. These components are interconnected within the overall system analysis(Staples et al., 2018) of the ecoinvent database in the background system (Wernet et al., 2016).

The life cycle inventories (LCIs) of the respective systems under study can be found in the Supplementary Material.

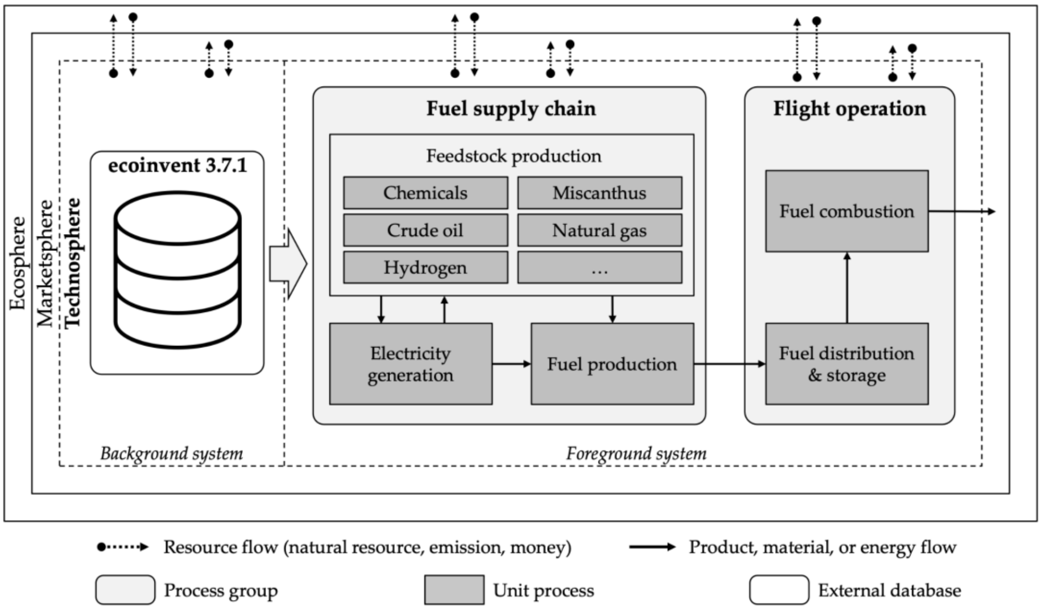


Figure 3. Foreground and background system within the system boundaries, including exchange! between the technosphere, ecosphere, and market sphere

Five distinct fuel varieties were examined in this investigation, encompassing traditional fossil kerosene and four variations of SAFs (refer to Table 1). The fossil kerosene supply chain commences with crude oil extraction (Sürer & Arat, 2017). The crude oil undergoes additional processing at a refinery through distillation methods and the addition of different additives (Biçer & Dinçer, 2017). Crude oil is believed to be extracted in Tyumen, Russia and then processed at a refinery in Hamburg, Germany (Giesen et al., 2014). The fossil kerosene was evaluated against four viable sustainable aviation fuels that were created using X-to-liquid methods, specifically through BtL and PtL pathways, as these pathways are the most extensively studied for industrial-scale production (Biçer & Dinçer, 2017). The synthesis procedures were founded on FTS (Section 2.1), which is also the most commonly employed technique in the field and has been extensively studied.

Table 1. Considered aviation fuels

Abbrevation	Description
Kerosene (fossil)	Fossil kerosene based on crude oil produced by refinery processes
Kerosene (bio_SMR)	Biokerosene based on miscanthus produced by steam methane reforming and Fisher-Tropsch synthesis
Kerosene (syn_SMR)	Synthetic kerosene based on hydrogen produced by steam methane reforming and Fisher-Tropsch synthesis
Kerosene (syn_PEM)	Synthetic kerosene based on hydrogen produced by polymer electrolyte membrane electrolysis and Fisher- Tropsch synthesis
Kerosene (syn_SOEC)	Synthetic kerosene based on hydrogen produced by solid oxide electrolysis and Fisher-Tropsch synthesis

The BtL route emphasizes the production of second-generation biokerosene using miscanthus as the feedstock, which is grown in Saxony, Germany (Giesen et al., 2014) further handled in Hamburg, Germany. The production of individual processes involves the refinement of biogas into biomethane by incorporating different additives, followed by conversion to hydrogen through steam methane reforming. In the subsequent stage of production, biokerosene is obtained using FTS (Doliente et al., 2020).

Three varieties of synthetic kerosene derived from hydrogen were explored in the context of the PtL pathway (Giesen et al., 2014). Regarding the initial synthetic kerosene, hydrogen is generated through the SMR process using natural gas, electricity, and water instead of biomethane. This sets it apart in terms of hydrogen production (Barke et al., 2022). Two other methods of production involve generating hydrogen through electrolysis. In this context, polymer electrolyte membrane and solid oxide electrolysis are utilized. With the PEM method, energy-intensive water splitting is used to exclusively produce hydrogen, requiring 55 kWh of electricity input per kilogram of hydrogen (NREL, 2019). The SOEC method operates in a similar manner, but it necessitates a small quantity of natural gas in addition to water and electricity (36.8 kWh electrical input per 1 kg of hydrogen) (NREL, 2018). Hydrogen is converted into kerosene using the Fischer-Tropsch Synthesis process. The entire production of synthetic kerosene occurs in Hamburg, Germany.

All feedstock materials, as well as the processed fuels, were transported using suitable means. The European pipeline network was utilized to cover the transportation distances to the refinery (Kim et al., 2021) At the airport, fuel is stored in tanks. The energy requirements for manufacturing fossil kerosene and the four varieties of SAFs were gathered from scientific literature and industry data (Doliente et al., 2020). Production expenses were determined using the energy required for production, the electricity cost specific to the country, and relevant scientific studies on the expenses related to SAF production (Schmidt et al., 2018).

When conducting the analysis of flight operations, a sample flight covering a distance of 2000 km with 160 passengers and their luggage was examined. This example represented a trip from Frankfurt am Main, Germany to Moscow, Russia. The total duration of the flight was 185 minutes, consisting of 45 minutes for take-off and ascent, and 140 minutes for cruising and landing. The analytical benchmark used in this study was the consumption per 100 passenger-kilometers traveled on a medium-haul flight spanning 2000 km with a load of 160 passengers (including luggage). According to information provided by Lufthansa Group, such an itinerary would require approximately 4.12 liters of kerosene (equivalent to specific energy usage of about 39.2 kWh) per every hundred passenger-kilometers (Sustainability in 2021 - fact sheet, 2021), The study included an analysis of fuel consumption. Information on the combustion characteristics of the fuels and their resulting emissions was taken from scientific research sources (Braun-Unkhoff et al., 2016),(Turner et al., 2011).

The study evaluated the impact using two different life cycle assessment methods, each focusing on a specific aspect of sustainability. The ReCiPe Midpoint method was employed as a widely used environmental assessment approach (Liu & Yang, 2020), and a life cycle cost-oriented method is utilized for the economic evaluation.

Seven impact categories were examined during the environmental assessment (refer to Table 2). In line with the Flightpath 2050 strategy goals, these included climate change and photochemical oxidant formation, as well as particulate matter formation and human toxicity due to health-related impacts. Fossil resource depletion was also studied because crude oil and natural gas, which are of fossil origins, are often used for electricity generation. Additionally, agricultural land occupation and mineral resource depletion were scrutinized in relation to cultivating bio feedstocks on agricultural land and the need for mineral resources in building refinery and synthesis plants. For the economic assessment, costs associated with fuel supply chain and flight operation were evaluated under life cycle costs. Revenues were not factored into consideration since they mainly depended on airline pricing strategies rather than directly correlating with the fuel utilized.

Table 2. Environmental and economic impact categories.

Dimension	**Impact Category**	**Unit**
Environmental	Climate change (CC)	kg CO2-eq.
	Fossil resource depletion (FRD)	kg Oil-eq.
	Particulate matter formation (PMF)	kg PM1o-eq.
	Agricultural land occupation (ALO)	m2 per year
	Photochemical oxidant formation (POF)	kg NMVOC-eq.
	Human toxicity (HT)	kg 1.4-DCB-eq.
	Mineral resource depletion (MRD)	kg Fe-eq.
Economic	Life Cycle Costs (LC)	US-Dollar

3. RESULTS

3.1. Overview of Impact Assessment Results

The impact category's lowest scores are emphasized, as discussed in Section 2.3. The study examined the use of four SAFs versus fossil kerosene on a medium-haul flight covering a distance of 2000 km, with results presented based on a functional unit of 100 pkm.

The combined findings indicate that utilizing the examined SAFs in place of fossil kerosene may lead to a decrease in certain environmental impact scores (such as CC, FRD, and HT), while also resulting in elevated environmental impacts in other categories as well as significantly higher LC.

Overall, the evaluation of the environmental effects shows that using SAFs would be beneficial, especially in reducing emissions harmful to the climate and health. However, fossil kerosene could also have advantages over SAFs due to their higher scores in other impact categories. For instance, the high scores for ALO are attributed to land demand for cultivating feedstock for biokerosene and the extraction and processing of various resources required to produce synthetic kerosene.

Concerning the economic impact of LC, it is evident that SAFs cannot yet achieve market penetration. The use of synthetic kerosene (PEM and SOEC) results in particularly high LC which exceed those of fossil kerosene by 786% and 588%, respectively. Economically semi-competitive is the use of biokerosene (SMR) and synthetic kerosene (SMR) which, however, lead to 196% and 149% higher LC, respectively. The key drivers of environmental and economic impacts are analyzed in more detail in Sections 3.2 and 3.3.

3.2. Detailed Analysis of the Environmental Impacts

When it comes to the economic influence of LC, it is clear that SAFs are not able to gain widespread use. The utilization of synthetic kerosene leads to notably high LC levels, surpassing those of fossil kerosene by 786% and 588%, respectively. Economically speaking, the use of biokerosene and synthetic kerosene is somewhat competitive.

In the case of biokerosene, a significant portion of the environmental impacts (between 83% and 98%) were directly linked to the fuel supply chain. For ALO, majority of these impacts stemmed from miscanthus cultivation (94%), while for PMF, POF, and FRD it was primarily due to FTS. The FTS process resulted in significant emissions including sulfur dioxide, volatile organic compounds, and particulate matter smaller than 10 μm accounting for most of the impacts. Furthermore, about 43% of the impacts came from upstream hydrogen chain which involved production of biogas as well as refining to biomethane. Similar impact contributions were observed in HT and MRD where energy demand during production steps played a substantial role.

For synthetic kerosene, the FTS process accounted for the majority of environmental impacts, ranging from 86% to 97%. The use of chemicals for gas purification and their upstream chains was a significant factor for ALO, HT, and MRD, contributing to 56–76% of the total impacts. Additionally, hydrogen production was found accountable for 7–26% of the environmental impacts in these cases. However, FRD showed a different pattern with natural gas extraction and processing accounting for 71% of its total impact. In terms of PMF and POF impact categories, emissions from the FTS process were responsible for most of the effects at 81-88%, including sulfur dioxide, volatile organic compounds,and particulate matter smaller than10 μm.

When it comes to synthetic kerosene, it showed poor performance in all impact categories except ALO. The significant energy demand during production was the primary cause of the adverse environmental effects, accounting for between 36% and 96% of the total impacts. This can be largely attributed to the current composition of the electricity mix, which still heavily relies on almost 50% fossil and non-renewable sources. As a result, the extraction, processing, and conversion of lignite, hard coal, and wood chips into electricity significantly contribute to environmental impacts.The use of synthetic kerosene resulted in particularly high environmental impact scores for several categories, including primary energy demand.

An exemption to this was seen in the category CC, where flight operation had a significant impact in addition to the fuel supply chain. For biokerosene and synthetic kerosene, it accounted for 93% and 76% of the total impact, respectively. This was due to the emission of GHGs from combustion, such as CO2, with approximately 2.5 kg being emitted per liter of fuel burned. In the case of synthetic kerosene, a similar amount of GHGs was emitted during combustion but only 20–26% could be attributed to flight operation. As discussed previously for other impact categories, this resulted from high energy demand in hydrogen production and electricity mix composition leading to large amounts of GHG release during extraction, processing, and conversion stages involved in obtaining non-renewable feedstocks.

When it comes to fossil kerosene, the fuel supply chain was found to be mainly responsible for the impacts in four out of seven environmental impact categories studied. For FRD, ALO, and MRD, it accounted for 74-96% of the total impacts. The primary driver of these impacts in all cases was crude oil extraction, contributing to 46-83% of the overall impact. In PMF fuel production (64%), as well as crude oil extraction played major roles in driving the impacts; however, 36% can also be attributed to flight operation and particulate matter emitted during this process. Flight operation had an even greater share in POF (60%), CC (70%), and HT (77%) impact categories. The combustion of fossil kerosene resulted in impacts driven by GHGs, particulate matter, and NO emissions. Overall, the analysis shows that the fuel supply chain was the primary driver of the environmental impacts of SAFs. In addition, energy-intensive production processes and the demand for fossil sources in electricity generation were often responsible for making them disadvantageous to fossil kerosene in some case.

3.3. Detailed Analysis of the Economic Impact

An exception to this occurred in the CC impact category, had a considerable influence in addition to the fuel supply chain. For biokerosene and synthetic kerosene, it accounted for 93% and 76% of the overall impact, respectively. This was attributed to the greenhouse gases generated from combustion.

Fossil kerosene had the lowest lifecycle cost at approximately USD 2.59 per 100 pkm, among all the alternatives considered. The lifecycle costs of all sustainable aviation fuels in the study were found to be between 149% and 786% higher than those of fossil kerosene. Across all fuels, it was observed that the fuel supply chain contributed significantly to around 98-99% of their total impact, with flight operation responsible for only about 1-2%. Fossil kerosene's lower lifecycle costs compared to SAFs can be attributed to its more developed and industrially implemented production processes. Despite being mainly responsible for nearly 98% of the total impact on lifecycle costs, this corresponds to just USD $2.53 per 100 pkm—considerably less than SAFs'. The primary driver behind fossil kerosene's lifecycle costs is crude oil processing into kerosene, accounting for approximately two-thirds of these costs; distribution and airport storage together contribute a mere fraction (only about 2%) towards its overall lifecycle impacts.

The most promising sustainable aviation fuels in terms of economic impact were biokerosene and synthetic kerosene, with costs of USD 7.66 per 100 km and USD 6.34 per 100 passenger-km, respectively. The higher costs for both biokerosene at USD 7.56 and synthetic kerosene at USD 6.34 in the fuel supply chain played a significant role in this outcome.

For biokerosene, these expenses primarily arose from miscanthus cultivation, gasification to produce biogas, and subsequent biomethane production used as feedstock for SMR—accounting for about 62% of the total cost. In more depth, similar to the preceding part, the overall effects are divided into the proportions linked to both the fuel supply chain and flight operation, as well as the primary factors influencing these impacts.

From an economic viewpoint, sustainable aviation fuels derived solely from renewable sources showed the poorest performance. Synthetic kerosene had the highest levelized cost at USD 22.94 and USD 17.82 per 100 passenger-kilometers, respectively. In this scenario, hydrogen production was the primary influencer, making up 87% and 83% of the total costs respectively. Specifically, a large portion of these expenses were related to energy requirements, which stood notably high at 55 kWh and 38 kWh per kilogram of hydrogen respectively, with an electricity price in Germany at USD 0.21 per kWh. At the current stage of market maturity for industrial hydrogen production based entirely on renewable sources, synthetic kerosene is economically non-competitive.

Overall, the economic evaluation indicates that Sustainable Aviation Fuels are not yet competitive with traditional kerosene. Without political interventions such as substitution, subsidy programs, or non-SAF tax measures, airlines will continue to favor the cheaper fossil fuels.

3.4. Influence of Using Electricity Based on Renewable Energy in Production

The previous examinations indicate that fossil kerosene outperformed SAFs in terms of economic impacts and, to some extent, also in terms of environmental impacts. The economic competitiveness of SAFs can be enhanced mainly through improved large-scale industrial production processes, which are expected to develop over time. However, SAFs already have some advantages in terms of environmental impacts. The analysis demonstrates that the energy demand and the use of electricity from fossil sources were often primarily responsible for negative effects. Shifting to an electricity mix based on 100% RE could further reduce the environmental impact of SAFs. This will be explored further in the following section where we examine replacing the electricity needed in the fuel supply chain with an electricity mix based on 100% REThe prior analyses indicate that fossil kerosene had economic and, to a certain extent, environmental advantages over SAFs. The competitiveness of SAFs in terms of economics can be enhanced through improved large-scale industrial production processes which are expected to develop gradually over time. However, SAFs already have some environmental benefits. The analysis reveals that negative impacts were often primarily attributed to energy demand and the use of electricity from fossil sources. Shifting towards an electricity mix based on 100% renewable energy could further reduce the environmental impact of SAFs. This aspect is explored further in the following section where the required electricity in the fuel supply chain was replaced with an electricity mix based on 100% renewable energy modeled after (Jacobson et al., 2017), who forecasted the electricity mix for the year 2050. The additional CIS to the scenarios can be found in the Supplementary Material. A comparison of the environmental and economic impacts of the two scenarios. In the following, the addition of "-RE" indicates energy carriers produced with renewable energy. In order to assess the viability of sustainable aviation fuel decarbonisation, it is crucial to consider the economic and environmental sustainability factors (Barke et al., 2022).(Jacobson et al., 2017), who predicted the electricity combination for the year 2050. The extra information about the scenarios can be located in the Supplementary Material. A comparison of the environmental and financial effects of the two scenarios. When "-RE" is added, it signifies energy carriers generated using renewable energy.

When it comes to environmental effects, utilizing an electricity mix entirely based on renewable energy lessens impacts on six out of seven categories related to SAFs. This reduction is solely attributed to decreased impacts on the fuel supply chain.

For biokerosene derived from renewable energy sources (SMR-RE), marginal enhancements of 1-2% were observed in impact categories such as PMF, ALO, and POF compared to biokerosene produced through steam methane reforming (SMR). Conversely, significant improvements of 16% and 24% were noted in impact categories related to climate change (CC) and fossil resource depletion (FRD), respectively, with an impressive 73% improvement seen in the impact category of human toxicity (HT). This indicates a notable advantage in utilizing this particular variant. Regarding synthetic kerosene, a distinction was necessary between hydrogen production methods via electrolysis and steam methane reforming (SMR). Synthetic kerosene derived from SMR-RE demonstrated only minor enhancements of 0.5-8% in impact categories like CC, FRD, PME, ALO, and POF compared to synthetic kerosene from SMR, except for HT, where a significant improvement of 22% was observed.

However, more substantial improvements were evident for synthetic kerosene derived from proton exchange membrane electrolysis (PEM-RE) and solid oxide electrolysis (SOEC-RE). Here, enhancements of 15-28% in impact categories like PMF and POR, and remarkable improvements of 71-97% in CC, FRD, ALO, and HT categories were achieved. This was primarily attributed to the elimination of fossil energy sources in electricity generation, consequently reducing negative environmental impacts associated with lignite, hard coal, and wood chains extraction and processing. Notably, the use of synthetic kerosene derived from PEM-RE resulted in a 90% reduction in CC impact compared to fossil kerosene, while SOEC-RE-based synthetic kerosene showed a 61% lower CC impact. Additionally, PEM-RE synthetic kerosene exhibited a 20% lower FRD impact than fossil kerosene.

In the case of synthetic kerosene, differences in hydrogen production methods had varying impacts. Minor improvements of 0.5-8% were seen for some categories when comparing SMR-RE and SMR synthetic kerosene types, while a significant 22% improvement was observed for HT. Much greater improvements were noted for PEM-RE and SOEC-RE synthetic kerosene types, with reductions ranging from 15% to as high as 97% across various impact categories due to the avoidance of fossil energy sources in electricity generation. These changes led to substantially lower environmental impacts by eliminating the extraction and processing of certain resources. Specifically, CC showed notable improvement due to low-emission hydrogen production and reduced CO2 demand in FIS systems within PEM-RE and SOEC-RE kinds, resulting in significantly lower CC impact compared to fossil-based options: up to 90% lower for PEM-RE and approximately 61% lower for SOEC-RE respectively. Additionally, FRD impact could be reduced by up to 20%.

When using an electricity mix based on 100% renewable energy, there was a decline in the impact category MRD due to the requirement for costly raw materials like copper and aluminum needed to build the renewable energy plants. This led to impact scores that were 4-124% higher, resulting in the unsuitability of SAFs for this category. The transition to a renewable energy-based electricity mix had no economic impact as it was assumed that the electricity price remained unchanged during the switch.

4. Discussion

The study's findings support the potential of SAFs to lessen the environmental effects of the aviation industry. While greenhouse gas emissions from flight operations remained similar, there was a notable decrease in NOx and particulate matter emissions. Additionally, significant amounts of CO2 were captured during fuel production, leading to reduced overall greenhouse gas emissions compared to fossil kerosene from a life cycle standpoint.

Based on existing production conditions and the current electricity mix, biokerosene shows significant promise as an alternative to fossil kerosene in terms of its environmental impact. However, challenges may arise from the cultivation of feedstock competing with agricultural land use for food production. Additionally, synthetic kerosene based on hydrogen generated by SMR or electrolysis is largely inferior compared to fossil kerosene. In the case of synthetic kerosene produced using SMR, this drawback is attributed to the necessity of natural gas as a feedstock. For synthetic kerosene produced through PEM and SOEC methods, high energy demand in hydrogen production combined with the current electricity mix composition are contributing factors.

Regarding the electricity mix, it is expected that renewable sources will see growing use for electricity generation in the future. This will also have a favorable impact on the production of SAFs. This prediction is backed by a scenario analysis conducted, which modeled an energy mix for 2050 based on previous work of (Jacobson et al., 2017),based entirely on renewable energy. The environmental effects of energy-intensive hydrogen production could be greatly minimized, leading to the production of synthetic kerosene with PEM-RE and SOEC-RE showing the lowest overall impacts in relation to climate change.

While the findings suggest that there is still room for economic improvement, the use of SAFs currently cannot compete with fossil kerosene due to significantly higher production costs. These costs are up to six times higher than those for fossil kerosene, which discourages their use in flight operations. This holds true for both scenarios involving the current electricity mix and a mix based entirely on renewable energy sources. Political interventions such as substitution, subsidy programs, or tax measures for non-SAFs will be necessary at this stage to enable cost-effective production of SAFs on a large scale and enhance their competitiveness.

At the same time, it is still uncertain if SAF production capacities can be expanded given the current electricity generation capabilities. The high energy requirement for hydrogen production through electrolysis could strain the electricity grid and lead to limitations in production. However, the energy-intensive nature of SAF production may help balance out fluctuations in renewable electricity supply.

There are additional unknowns regarding the fuels studied and how they are produced. The study concentrated on second-generation biokerosene and synthetic kerosene based on hydrogen. Different methods for hydrogen production, such as SMR, PEM, and SOEC, were looked into. However, there is also research exploring third-generation biokerosene (Klein et al., 2018) other methods of hydrogen production such as methane pyrolysis(Schneider et al., 2020). FTS was considered the dominant synthesis process in this study because of its advanced stage in the market. However, alternative synthesis processes like methanol production and methanation could be examined in future studies. It would be intriguing to explore the synthesis of ammonia-based fuels using Haber-Bosch processes given their carbon-free nature, which results in no CO emissions during combustion. Additionally, an analysis of biokerosene production through HEFA, HTL, AtJ, and DSHC methods could also be valuable.

A significant source of uncertainty in this study is due to the limited spatial variability. When considering SAFs, it was assumed that production occurred solely in Germany and that input materials also came from there. Exploring various supply chain setups within a more comprehensive spatial differentiation can lead to actionable insights for optimizing supply chain configurations.

Moreover, the research concentrated on fuels that can be seamlessly incorporated without modification. There are alternative fuels such as alcohols (e.g., ethanol and methanol) and liquid hydrogen, which necessitate modifications to the powertrain and fueling infrastructure. The study did not explore how these alternatives could offer advantages over drop-in fuels and traditional kerosene.The mentioned elements can be taken into account in future research to expand the conducted study. This will allow for a thorough comparison of potential aviation fuels. To fully assess the viability of sustainable aviation fuel decarbonisation, it is important to consider various aspects (Barke et al., 2022).

5. Conclusions and Outlook

This research examined the possibility of replacing fossil kerosene with various types of SAFs on medium-haul flights. It involved an analysis of the environmental and economic effects of using SAFs compared to fossil kerosene, through conducting assessments in these areas and identifying their respective advantages and disadvantages. The study specifically emphasized the fuel supply chain and flight operation during usage.

The study findings indicate that SAFs may offer some environmental benefits. However, given the current level of development and existing production conditions, fossil kerosene is still the preferable option. In terms of economic impact, SAFs are not yet cost-effective and require support through political measures such as substitutions, subsidies, or tax incentives to promote their usage. The high energy demand in fuel production and reliance on fossil sources in the current electricity mix are key drivers behind the negative environmental and economic impacts.

However, this composition is expected to gradually prioritize a higher proportion of renewable energy in the long run. Further scenario analyses revealed that using a 100% renewable energy-based electricity mix could significantly decrease environmental impacts in six out of seven investigated impact categories. It's particularly noteworthy that sustainable aviation fuels, which require high energy for production, have become environmentally competitive with fossil kerosene. The only category showing deterioration was MRD due to the construction of RE plants. Consequently, SAFs produced by renewable energy can play a role in reducing environmental impacts within the aviation sector and contribute to achieving the goals set out in Flightpath 2050.

This research could serve as a starting point for future studies. The findings provide an outline of the environmental and economic consequences of various aviation fuels, facilitating a comprehensive comparison. Subsequent research should include additional fuel types, such as third-generation biokerosene or SAFs manufactured by HEFA, HTL, AtJ, DSHC, or StL. In this context, diverse synthesis methods must be taken into account as well as alternative production routes for fuels and necessary feedstocks (e.g., hydrogen). This approach can assist in early identification of the most promising SAFs and concentrate further studies on them.

In addition, it is important to analyze spatial differences, particularly in the fuel supply chain. On one hand, countries that have a higher proportion of renewable energy sources in their electricity mix may benefit from producing SAFs (and vice versa). Additionally, countries with low energy costs can provide economic advantages. By considering these factors and implementing more advanced spatial differentiation in the fuel supply chain, configurations that result in lower environmental and economic impacts can be developed. However, less developed countries face challenging working conditions and there may be conflicting objectives among the three pillars of sustainability. Therefore, it is essential to integrate a social analysis.

While sustainable aviation fuels can play a role in creating a more environmentally friendly aviation sector in the immediate future, it is crucial to incorporate new aircraft propulsion technologies for long-term sustainability goals.by Barke et al. (Barke et al., 2021),(Barke et al., 2020). Non-drop-in fuels, such as liquid hydrogen, necessitate adjustments to the powertrain and the utilization of innovative propulsion technologies like battery-based or fuel cell-based concepts. Both strategies are essential for meeting the aviation sector's long-term emission reduction targets. Taking into account various market entry times will enable the creation of pathways towards achieving a sustainable aviation industry that considers short-term and long-term sustainability goals.

Overall, this article contributes to the scientific literature by generating new LCI datasets for a comprehensive assessment of fossil kerosene and four different types of SAFs. The comparative environmental and economic analysis has identified particular areas in the production and utilization of SAFs that can be addressed in fuel development. This ultimately supports the creation of aviation fuels that are both environmentally beneficial and economically competitive. Therefore, this study lays the groundwork for further examinations of SAFs and can be expanded upon in future research as mentioned earlier.

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