Innovations

The Future of Sustainable Aviation Fuels

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Abstract: The possibility of using alternative energy sourcesin aviation has been widely discussed in recent years due to the need to reduce carbon dioxide emissions into the atmosphere, as well as the desire of many countries to achieve carbon neutrality.While much research has focused on technological opportunities and resource availability for producing sustainable aviation fuels, less attention has been paid to comparing the prospects of different fuels. This study aims to address this gap by evaluating the prospects and forecasting the use of alternative aviation fuels in the short, medium and long term. We present a comparative analysis of the potential use of various alternative energy sources in the aviation industry. Through bibliometric and SWOT analysis, as well as an examination of case studies of international initiatives at different levels (national, industry, corporate), and foresight projects, the prospects of alternative aviation fuels are assessed. The study has identified promising types of aviation fuel with the potential for large-scale use in the coming years, as well as a set of factors that hinder a rapid and complete transition to alternative fuels.

Keywords: Aiation fuel, alternative fuel sources,biofuel, synthetic kerosene, liquid hydrogen, electric aircraft

1. Introduction

In the modern world, people are highly mobile and regularly use various modes of transport, most of which run on liquid fuels produced from oil. Alternative fuels such as synthetic, electric or biofuels already exist, but they still have disadvantages, including limited resources and high emissions of carbon dioxide and other pollutants. In aviation, this problem is especially relevant, since gas emissions negatively affect the radiation balance of the earth's atmosphere (Lee, 2009).For instance, the global aviation fuel market was valued at 177.3 billion USD in 2021 and may reach 654.8 billion USD by 2029 (Fortune Business Insights, 2022). Global fuel consumption by commercial airlines has increased every year since 2009, reaching a record high of 95 billion gallons in 2019 (Statista, 2022a) in line with the growth in carbon dioxide emissions: commercial aviation alone generated 905 million metric tons of carbon dioxide in 2019 (Statista, 2022b). After 2019, these values declined due to the effects of the coronavirus pandemic, but there is already a trend toward recovery in traffic volumes.

In recent years, the issue of switching to more environmentally friendly types of aviation fuel has become increasingly relevant.At the 77th IATA Annual General Meeting the member airlines approved a resolution committing to achieve zero carbon emissions by 2050 (IATA, 2021). Sustainable aviation fuel currently makes up less than 0.1% of all aircraft fuel used (World Economic Forum, 2022). IATA estimates that sustainable aviation fuels can provide about 65% of the emission reductions needed for the aviation industry to achieve net zero by 2050 (World Economic Forum, 2022). Moreover, the improved energy properties of certain alternative aviation fuels can increase the flight range (Daggett et al., 2007; Holladay, 2020) and cargo capacity and save fuel (Holladay, 2020; Energy.gov, 2020b; Detsios, 2023), and thus, ceteris paribus, increase the availability of flights and carriers' profit margins.This gives grounds to expect a transformation in the aviation fuel market and a significant increase in the use and production of green aviation fuel, despite the laboriousness of this process (Searle et al., 2019).

There are various approaches to defining sustainable aviation fuel (SAF), based on the regulatory context and raw materials and technologies deemed to be particularly important. The United States (US) Department of Energy defines sustainable aviation fuel as a biofuel applied to power aircraft, with properties similar to those of conventional jet fuel but with a lower carbon footprint (Energy.gov, 2020a). In relevant European Union documents (European Commission, 2021) and in literature (Yilmaz et al., 2017; Goh et al., 2022), bio- and synthetic fuels are seen as those that supplement or replace conventional aviation fuel.[1] Finnair defines sustainable fuel as a renewable fossil fuel substitute that can be blended with conventional aviation kerosene, which indicates its bio- and synthetic nature (Finnair, 2023). The marketing firm MarketsandMarkets considers bio- and synthetic fuels and hydrogen as sustainable fuels (Markets and Markets, 2022). In this paper, sustainable aviation fuel is understood as fuel produced (obtained) from materials or substances other than conventional sources (IATA, 2022).

The existing research in this area are mostly focused on specific sustainable fuel development areas, while the prospects for various fuels types, and their comparison receive less attention. The present study is carried out to fill this gap. Therefore, the purpose of this article is to analyze the prospects for the development of alternative types of aviation fuel in the short and medium term.

[1] Here and below, synthetic fuels produced from hydrocarbon raw materials are not considered.

The article consists of sixsections, including introduction. Section 2 defines the research context for SAF, and Section 3 then develops the research methodology, including methods and steps of analysis and testable research hypotheses. Section 4 contains results of SWOT analysis for each type of alternative fuel, an overview and analysis of foresight studies (the United Kingdom, Germany, Sweden, Mexico, Brazil). Section 5 is devoted to the discussion and the comparativeanalysis of these documents. Section 6 includes the main conclusions of the implemented study.

2. Literature Review

According to forecasts, there is an increase in the use of traditional fuels, which are not environmentally friendly and harmful to the state of the planet. The projected growth in air travel and trade will have significant environmental consequences (Shahriar, 2022). Reducing CO2 and overall greenhouse gas emissions in the aviation sector can be achieved either by reducing demand or through technological means (increasing fuel efficiency, developing alternative energy sources).Alternative energy may be a feasible solution to this problem, as CO2 emissions from burning SAF in aircraft engines are roughly equivalent to the CO2 emissions observed in biomass production plants (Blakey, 2011).SAF is an attractive alternative to fossil jet fuel because it has nearly identical physical and chemical characteristics to conventional fuel while meeting several sustainability criteria (Doliente, 2020). The benefit of SAF is the significantly lower carbon dioxide emissions compared to traditional fuels, and even partial replacement of traditional jet fuel with SAF significantly reduces overall CO2 emissions in the aviation sector (Bittner, 2015; IATA, 2021; Shahriar, 2022). Also, switching to SAF has many positive aspects, whichMd Fahim Shahriar writes about. These are future energy security and economic independence (the transition to SAF can mitigate the risks of supply chain disruptions), diversity of energy sources(Shahriar, 2022).

However, SAF can only be useful if it can be easily used in modern aviation systems and provide long aircraft life (Bittner, 2015; Shahriar, 2022). There are also technological problems (such as the need to duplicate the infrastructure for providing fuel and engines), problems with the cost of synthetic fuel, institutional and legal barriers (Scheelhaasea, 2019).Currently, there is a growing number of scientific studies devoted to assessing the possibilities of overcoming these barriers (Scheelhaasea, 2019; Zhang, 2020; Dodd, 2021), studying biofuels and its development in general (Ng, 2021), development of strategies for their implementation (Ng, 2021; Tanzil, 2021), assessment of environmental effectiveness implementation of SAF (De Jong, 2017; Capaz, 2021), economic effects (Martinez-Valencia, 2021), infrastructure readiness for its implementation (Shahriar, 2022; Martinez-Valencia, 2021). Most studies are focused on exploring such types of alternative fuels as hydrogen (Surer, 2018; Baroutaji, 2019; Yusaf, 2022), electricity (Madonna, 2018; Barzkar, 2020; Cano, 2021), biomass and green energy (Wei, 2019; Wang, 2019; Shahabuddin, 2020), as well as synthetic fuels (synthetic kerosene) (Colelli, 2023),and other types of alternative aviation – liquefied natural gas (LNG) based, ammonia based, solar aviation, methanol and ethanol (Su-ungkavatin, 2023).

This article discusses the most optimal fuels for future use (ibid), which include biofuels, synthetic kerosene, liquid hydrogen, hydrogen fuel cells and electricity.

3. Methodology

3.1 Stages of analysis

The purpose of this study is to analyze the prospects for the development of alternative types of aviation fuel in the short and medium term. To achieve it, approaches to defining environmentally friendly fuels, the current world situation with the transition to alternative energy sources, as well as the limitations and driving forces of this process are considered. The key methods of analysis arebibliometric analysis, SWOT analysis, case studies of international initiatives at various levels (industry, corporate), and an analysis of foresight projects carried out to assess the prospects for alternative aviation fuels.

Key stages of analysis and their rationale:

1) Bibliometric analysis to identify promising research areas in the field of alternative fuels.

2) SWOT analysis of alternative fuel types to compare their key characteristics, strengths and weaknesses, and development opportunities (Tables 1-5).

3) Review of foresight studies to identify independent expert opinions on the alternative aviation fuels' prospects. Foresight projects implemented in regions that have adopted particularly ambitious sustainable aviation fuel targets were selected for analysis (EU countries, the UK), along with Brazil and Mexico which are actively integrating into the global sustainable aviation fuel agenda due to having a significant acreage of arable land that can be used to produce biofuels.

3.2 Research Hypotheses

We propose the following research hypotheses and the rationale for their formulation.By 2025, only between five billion (IATA, 2022) and 18 billion (IEA, 2019) liters of sustainable fuel will be available to the global aviation industry; by 2040 the supply will increase to 75 billion liters (ibid). The demand for aviation fuel is predicted to reach 371 billion liters by 2025, and 390 billion liters by 2040 (IEA, 2019). In the next few decades, the supply of sustainable aviation fuel will not meet industry demand.

Hypothesis 1: Sustainable fuels can only be fully applied in the aviation sector in the long term.

Large-scale production of bio- and synthetic fuels has not yet been established. For instance, the world's first commercial green synthetic kerosene plant (excluding pilot plants) was launched in Germany in 2021, and its production capacity is quite modest: less than 1.300 liters (336 gallons) per day, or 470.000 liters per year (Euronews, 2021). A significantly larger capacity plant (50.000 tons) is not scheduled to come online until 2027 in the Netherlands (Amsterdam, 2021). It is also worth noting the low level of production of "green" electricity. At current growth rates, Europe (one of the world leaders in green electricity production) will not reach its target share of renewable electricity of 69% by 2030 (according to the REPowerEU plan (European Commission, 2022)) (IEA, 2022a). In most other regions, the values of the corresponding indicators are even more modest. Until 2030, the use of carbon as a feedstock for the production of synthetic fuels will be very low (IEA, 2022b). Synthetic fuel prices also depend on the type of electricity generation and are projected to be two to six times higher than the price of carbon kerosene by 2030 (TNO Publications, 2020). The global production of aviation biofuel is expected to reach between two billion and six billion liters by 2026, which is out of proportion with the overall demand for aviation fuel (371 billion liters in 2025 (IEA, 2021)). In addition, given the limited supply of possible resources and challenges in processing them (e.g. waste), the biofuel industry needs to optimize its supply chain (IRENA, 2021b).

Hypothesis 2. In the medium term, bio- and synthetic fuels will be actively applied, but only as "additives" to conventional fuels.

The aviation sustainability issue will remain on the agenda despite the arising problems. The signatories of the Convention on International Civil Aviation strive to secure their permanent and sustainable participation in the international air transport system (ICAO, 2007). To reduce carbon emissions while maintaining the availability of air travel, countries will be introducing regulations to require blending alternative liquid fuels with conventional aviation kerosene (as did, e.g., the European Union) (Council of the European Union, 2022).The number of active commercial aircraft in the world is estimated at 28.600 (Ch-aviation, 2022). It will not be possible to upgrade this fleet quickly to create the market for new fuel types.

Hypothesis 3. Until the middle of the century, hydrogen and electricity will not be applied in commercial aviation at all, or their application will be very limited.

Even if technologies for the successful application of hydrogen and electricity as aircraft fuel are developed soon, their implementation directly depends on the aircrafts' technical ability to "consume" them. Due to the absence of such aircraft, the aviation industry will have no demand for hydrogen and electricity in the first half of the 21 century.

To test these hypotheses, various types of foresight project reports on alternative types of aviation fuel were analyzed.

4. Results

4.1 Bibliometric Analysis

In the scientific community, the number of studies on alternative aviation fuels increases every year, which is confirmed by our bibliometric analysis. In recent years, the number of publications on this topic increased from nine in 2010 to 363 in 2023, respectively (Figure 1).

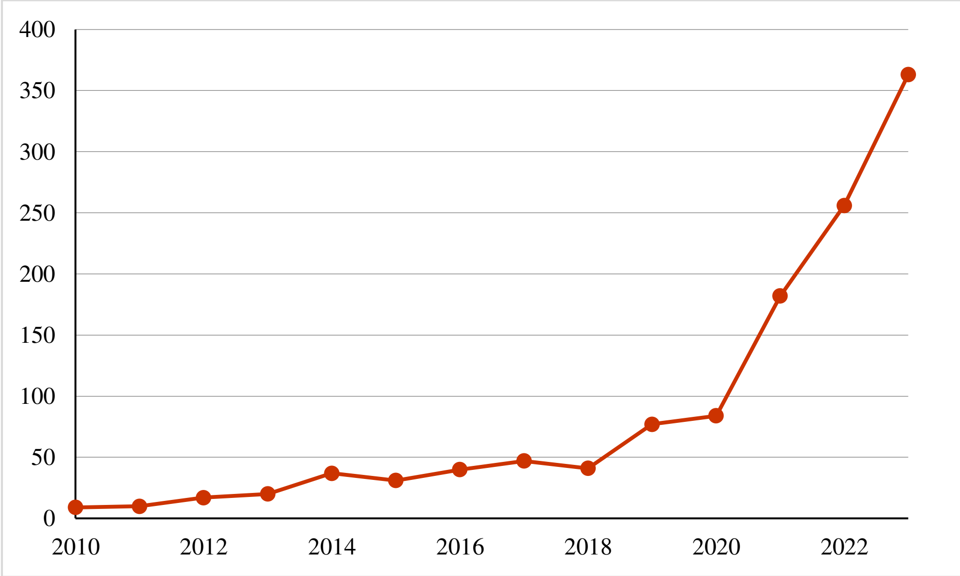

Figure 1. Growth of Publication Activity on the Topic in 2010-2023

Note: The ScienceDirect database was searched using the query "alternative jet fuel" OR "sustainable jet fuel" OR "green jet fuel" OR "decarbonization of aviation" OR "climate neutral aviation" OR "aviation sustainability" OR "reducing emissions from aviation" OR "sustainable aviation fuel"; the search yielded 1269 results.

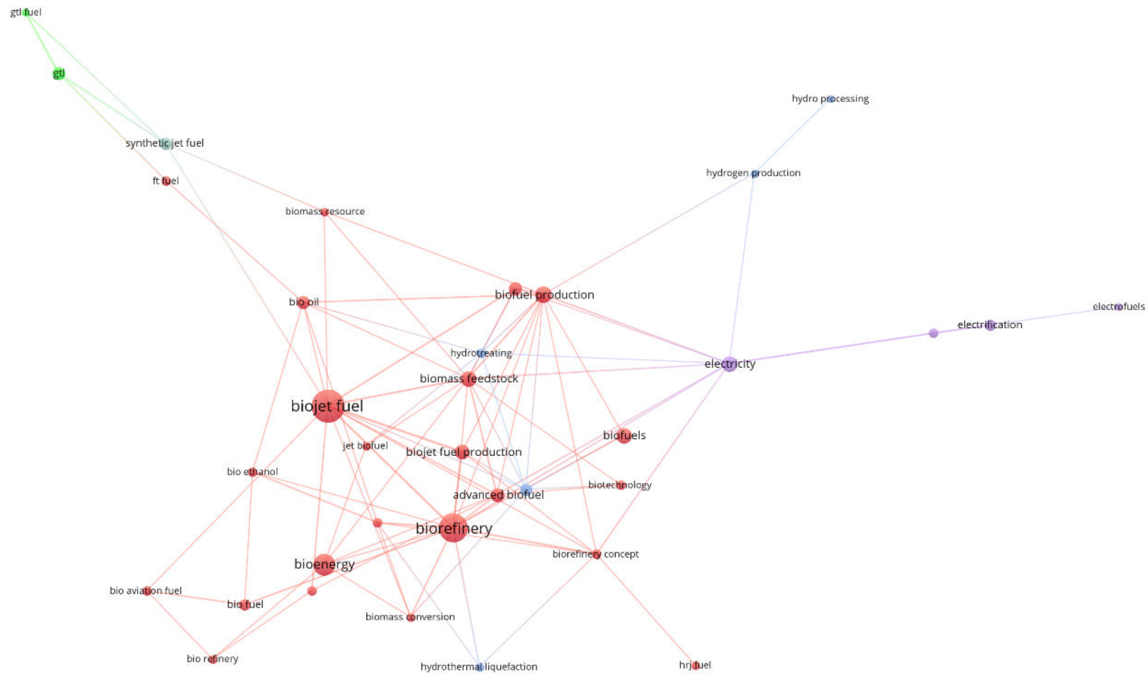

Figure 2. Semantic Map on «Alternative Aviation Fuel Types»

Note: The ScienceDirect database was searched using the query "alternative jet fuel" OR "sustainable jet fuel" OR "green jet fuel" OR "decarbonization of aviation" OR "climate neutral aviation" OR "aviation sustainability" OR "reducing emissions from aviation" OR "sustainable aviation fuel"; the search yielded 1269 results. The obtained data was processed using VOSviewer.

To analyze the research agenda in the field of alternative fuel types, a semantic analysis of publications on this topic which have appeared between 2010 and 2023 was carried out (Figure2). The analysis generated a list of the terms most frequently used in publications (more than 1200 in total). From this list, terms were extracted that refer to specific alternative aviation fuel types (36 words), in particular bio- and synthetic fuels, hydrogen, and electricity.The review of the sustainable fuel research agenda revealed diverse interest in biofuels and other relevant fuel types. For example, the existing biojet engines-related studies can be broken down into the following areas: production methods, feasibility, and environmental analysis, among others. Availability, sustainability, and suitability of raw materials to meet the growing demand for biofuels remain a challenge, despite the fact that various ways to produce them have been developed (Alherbawi, 2023).

Value engineering studies show that the use of biofuel increases the engine's energy efficiency by 18.2% compared to kerosene. The environmental damage costs (or environmental and economic parameters of the engine) decrease from 59.300 USD per year to 39.000 USD (Akdenis et al., 2023). Khalifa (2022) modelled the optimal ratios for blending jet biofuels with conventional kerosene.Mohideen (2023) assessed the scope for reducing energy consumption in aviation by switching to alternative fuels such as liquefied natural gas (LNG) and/or liquid hydrogen (13-21% smaller environmental impact than that of conventional kerosene).As for synthetic fuels, (Pio et al., 2023) note the need for large-scale deployment of PtL (power-to-liquid) plants to manufacture alternative fuels, for their subsequent application in line with the completely carbon-free cycle principles.

Thus, the analysis of the research agenda highlights the relevance of such areas as the introduction of biofuels, synthetic fuels, and hydrogen as alternatives or "additives" to kerosene. In particular, production methods are being studied and such fuels' effects on performance characteristics evaluated. However, short- and medium-term development prospects for sustainable aviation fuel are addressed less frequently. This study fills this gap and assesses the aviation industry's potential to transition to alternative fuels based on current key industry and global trends. The first step is to analyze research on each type of alternative fuel, and present its strengths, weaknesses, opportunities and threats (SWOT analysis).

4.2 Analysis of the Strengths and Weaknesses of Alternative Sustainable Aviation Fuels

Biofuel

By now, the American Society for Testing and Materials (ASTM) has certified at least seven manufacturing approaches based on various biological raw materials (Alherbawi, 2023). Materials such as oilseeds (Wang, 2020; Tan, 2020), corn (IRENA, 2021a), sugar cane (Capaz et al, 2021), and algae (Guo, 2017) can be used to produce biofuel. In addition to crops, various kinds of waste generated from their processing can be used to make biofuel, such as used vegetable oil (Ahmad, 2021), rice hulls (Chen, 2020), forestry residues, woodworking waste (Energy.gov, 2020), and municipal solid waste (ibid). Animal fat can also be used for biofuel production (NASA, 2011).

Biofuel development is mainly driven by its environmental characteristics, the lack of commercially viable technologies to apply other alternative aviation fuels, and government policy initiatives to reduce carbon emissions, including financial support for the use of biofuels (Lim, 2023). Also, subject to certification, the use of biofuel doesnot require significant structural changes in aircraft.

Two major, and interconnected, problems with biofuel are its costs and limited supply. On average, biofuel's cost is two to four times higher than that of conventional aviation kerosene (ibid), and even higher price difference estimates are cited in literature (seven to eight times more expensive) (ibid).

The global availability of raw materials is difficult to assess because many regions lack sufficient amounts of biomass for the commercial production of biofuel (ibid). Algae are considered the most viable option for biofuel raw material (Yang, 2016). Algae can be grown in open reservoirs and enclosed photobioreactors alike. They can be cultivated in marine, fresh, brackish, and waste waters (Khan, 2023). But there are also limitations on the use of algae for biofuel production, which currently do not allow for the large-scale implementation of this practice.

Producing biojet fuel from microalgae biomass is a complex and costly process. Extracting lipids from harvested biomass is also energy-intensive. Some researchers believe the catalytic hydrothermal liquefaction process has the greatest potential for converting algae biomass into biofuel, due to better energy efficiency (there is no need to pre-dry the biomass) (Khan, 2023). Only certain strains of algae must be used for the commercial application of such fuel, which requires additional investment in new research (Sydney et al., 2019).

Table 1. SWOT Analysis of Biofuel's Application

Strengths	**Weaknesses**
Good environmental properties	High production costs compared to hydrocarbon fuels
Can be applied without replacing aircraft and infrastructure	Complex production processes
A wide range of suitable bioresources	Insufficient production output
Practical experience of application in aviation is accumulated	Certification requirements
One of the cheapest alternative fuels	Need for further research for commercial application
Can be blended with hydrocarbon fuels	No aircraft certified for 100% use of biofuels yet
Opportunities	**Threats**
No commercial technologies to apply other alternative aviation fuels	Lack of bioresources in certain countries and regions
Implementation of green public policies	Reduced prices of conventional aviation kerosene

The above table is the result of a SWOT analysis and reflects the main strengths, weaknesses, opportunities and threats of biofuels in aviation.

Synthetic Kerosene

Synthetic kerosene is made by combining captured carbon with green hydrogen produced from water using renewable energy sources (Shell, 2021). The advantage of this fuel is that it allows for the use of existing infrastructure and, since it can be blended with conventional aviation fuel, a gradual transition to synthetic fuel becomes possible (Schmidt et al., 2016).

At the same time, when applied on a large scale, synthetic fuel has a number of limitations. The key barrier is price. For example, according to the European Commission, synthetic fuel is 5.7-8.1 times more expensive than conventional kerosene (European Commission, 2020). By 2050, Ludwig-Bölkow-Systemtechnik companyexpects a significant reduction in synthetic fuel's production costs, but even then, its price will be almost twice that of conventional fuels today (Schmidt et al., 2018).

There are also otherlimitations such as the need for manufacturers to obtain fuel certifications (which is an arduous process), and invest in the research and development of new production technologies (e.g., renewable energy-based water electrolysis, carbon capture, and actual fuel production processes) (European Commission, 2020).

Table 2. SWOT Analysis of Synthetic Kerosene's Application

Strengths	**Weaknesses**
Good environmental properties	High production costs compared to hydrocarbon fuels
Can be applied without replacing aircraft and infrastructure	Lack of green energy
Practical experience of application in aviation is accumulated	Current amounts of captured carbon are low
Can be blended with hydrocarbon fuels	Need to invest in new technologies
Opportunities	**Threats**
New application areas for carbon capture technologies	Reduced prices of conventional aviation kerosene

The above table is the result of a SWOT analysis and reflects the main strengths, weaknesses, opportunities and threats of synthetic kerosenein aviation.

Hydrogen (in a liquid state)

Hydrogen-powered aircraft release no carbon providedthat green hydrogen is applied (which requires sufficiently large-capacity renewable energy sources and hinders hydrogen production directly at airports), so a completely carbon-free cycle is created (Project NAPKIN, 2022). In liquid form, hydrogen contains about 2.5 times more energy per kilo than aviation kerosene (Najjar, 2013), with a lower density (70.85 kg/m^3 vs. 810 kg/m^3) (Harsha, 2014). Hydrogen changes from gaseous to a liquid state at 253°Cbelow zero (Airbus, 2021). Special storage tanks are required to maintain such a low temperature, which are being developed by aircraft manufacturers. Though cryogenic tanks for liquid hydrogen storage are successfully used in the space industry, replicating them in aviation is not possible since hydrogen storage tanks for commercial aircraft will have to withstand approximately 20.000 take-offs and landings (Airbus,2021). In the development of such tanks special attention is paid to insulation, to prevent hydrogen evaporation and thus increase the performance and safety of hydrogen-powered aircraft (Khandelwal, 2013). Cryogenic tanks are bulky, and when used to store hydrogen fuel they cannot be placed in the wings (as fuel tanks in kerosene-powered aircraft) due to their thickness, which degrades the aircraft's aerodynamic performance. To achieve maximum structural and thermal efficiency, their shape should be spherical, but given the sphere's poor aerodynamics, a cylindrical shape is considered best (Harsha, 2014). On the other hand, the familiar aircraft engine design needs to be changed only slightly (Detsios, 2023).

Despite the stereotypes about the use of hydrogen being unsafe, this cannot be unequivocally confirmed on the basis of the substance's characteristics. The biggest safety issue with hydrogen is detecting and minimizing leaks (Harsha, 2014). There is also the airport safety issue during the handling and storage of hydrogen: to reduce the likelihood of a chain reaction in the event of an explosion of a hydrogen tank, infrastructure facilities must be located at sufficient distances from each other (Kearney, 2021).

Table 3. SWOT Analysis of Hydrogen's Application (in a liquid state)

Strengths	**Weaknesses**
Good environmental properties	Currently there are no commercial technologies
	Aircraft design and infrastructure must be modified
Fully carbon-free cycle can be achieved	Hydrogen is perceived as unsafe
	Insufficient green energy supply
High energy efficiency	Hydrogen production at airports is limited due to the energy intensity of the process
Opportunities	**Threats**
With the development of green energy, the cost of hydrogen can become relatively low	Accidents affecting public opinion
	Reduced prices of conventional aviation kerosene

The table based on the results of the SWOT analysis reflects the main strengths and weaknesses, opportunities and threats of liquid hydrogen in aviation.

Hydrogen Fuel Cells

Hydrogen fuel cells are devices that burn hydrogen to produce both heat and electricity. In this paper hydrogen fuel cells' operation principle is described using the proton-exchange membrane fuel cell as an example. It is the most common polymer-electrolyte membrane fuel cell (PEMFC). Its main components are two electrodes, a proton exchange membrane, bipolar plates, and gas diffusion layers. Gaseous hydrogen emits electrons at the anode, leaving behind protons which can pass through the proton exchange membrane. Gaseous oxygen molecules merge with protons and electrons on the cathode side. The redirected electrons power the electric motor. The reaction's end product is water, with no greenhouse gases emitted (Yusaf, 2023).

Fuel cells' high energy efficiency and low risk of system failures should be noted.

In addition to the drawbacks associated with the production and storage of hydrogen (Colozza, 2002), it is worth mentioning that many fuel cell technologies are still at the prototype stage, and their implementation costs are high (White, Oleksiewicz, 2023).

Table 4. SWOT Analysis of Hydrogen Fuel Cells' Application

Strengths	**Weaknesses**
Good environmental properties	Currently there are no commercial technologies
	Aircraft design and infrastructure must be modified
Fully carbon-free cycle can be achieved	Hydrogen is perceived as unsafe
	Insufficient green energy supply
High energy efficiency	High implementation costs
Opportunities	**Threats**
With the development of green energy, the cost of hydrogen can become relatively low	Accidents affecting public opinion
	Reduced prices of conventional aviation kerosene

The table based on the results of the SWOT analysis reflects the main strengths and weaknesses, opportunities and threats of using liquid hydrogen fuel cells in aviation.

Electricity

The only power source for fully electric aircraft (there are also turboelectric and hybrid electric ones, but these also have gas turbine engines, so their carbon emissions are only slightly lower than those of carbon kerosene-powered aircraft) is a rechargeable battery connected directly to the electric motor (Adu-Gyamfi, 2022). Unlike the hybrid architecture, this configuration does not allow for inflight battery charging, so they must be charged on the ground before the flight. Thus, the overall carbon emissions effect will largely depend on the source of electricity used to charge the batteries.

While all-electric aircraft have many advantages including zero emissions, low noise, and reduced operating costs, battery technology has not yet sufficiently matured to fly the same distances as jet fuel aircraft (Epstein, 2019).

Table 5. SWOT Analysis of Electricity's Application

Strengths	**Weaknesses**

Good environmental properties	Currently there are no commercial technologies
Fully carbon-free cycle	Aircraft design and infrastructure must be modified
Low noise	Insufficient green energy supply
Opportunities	**Threats**
Possibility of creating hybrid aircraft	Electric aircraft cannot fly long distances

The table based on the results of the SWOT analysis reflects the main strengths, weaknesses, opportunities and threats of using electric aircraft.

4.3 Analysis of Foresight Studies

The UK

According to the Sustainable Aviation Strategy (Sustainable Aviation, 2020) developed by the organization of the same name jointly with British commercial companies, by 2035 annual sustainable fuel consumption will reach between 14.5 million and 30.9 million tons, or between 4% and 8% of the total global consumption of aviation fuel. The study focused on building roadmaps for the introduction of green aviation fuel.

Biofuels and synthetic kerosene are currently seen as green fuels, but biofuel is expected to have the highest growth in consumption by 2035.By 2050, long-range aircraft will be able to fly on totally different energy sources, such as, e.g., hydrogen and electricity.

By 2035,UK-produced aviation fuel could meet between 3.3% and 7.8% of the country's total demand. By 2050, 32% of the UK's aircraft fuel demand (4.5 million tons) could be met with domestically produced green fuel. Between 2025 and 2035, the production of sustainable aviation fuel in the UK will annually grow by 34-44%. By 2035, the export market will reach about two billionpounds.

The goals of the document under consideration included forecasting sustainable fuel's potential production outputs globally and in the UK until 2050; estimating the levels of decarbonization and the level of UK fuel security with the introduction of alternative aviation fuels; demonstrating the market potential of advanced green fuels to producers, refiners, investors, and other stakeholders; estimating the industry's job creation potential; and assessing the possible synergy between the industry and the government; and, finally, the growth of the UK's export potential.

Germany

In 2019, a foresight study of the role of biofuels in the German transport sector was conducted (Millinger, 2019). According to it, until transport in Germany (including aviation) is electrified, biofuel will remain the most promising alternative to fossil fuels. Since the country'sown resource availability is limited and the sustainability of using crop-based biomass for bioenergy production is questionable, electrification remains the only major alternative. The scenario analysis method was applied in the course of the study to consider the various options for reducing greenhouse gas emissions and assess the role of biofuels in the process.

Sweden

To implement the Swedish Aviation Strategy, a foresight study was conducted in 2021 (Norrman, Talalasova, 2021). Its goal was setting up a long-term national platform to bring together aviation stakeholders and create a synergy with successful research and innovation institutions. The foresight project was focused on identifying the steps required to help the Swedish aviation industry abandon fossil fuels: domestic aviation will stop using them by 2030, and after 2045, no flights departing from Swedish airports will be powered hydrocarbon fuels. The main methods of the study included trend analysis, scenarios, and roadmaps. Thematically, the study covered three areas: thegrowth of the liquid green fuel market (including biofuels and synthetic fuels); development and implementation of alternative technological solutions (hydrogen-, electricity-powered, and hybrid aircraft); and the growth of other markets (including the emergence of new business models and communication methods).

Abandoning fossil fuels will require investments in the production and application of biofuels and in the electrification of air transport. For these purposes, Sweden plans to use public-private funding models, among other things, to fund research projects. Providing alternative fuel to aviation is seen as a four-stage process.

In 2020-2025, the focus will be on research projects covering the following topics: the development of fuel cells and assessing the feasibility of hydrogen engines; developing aircraft batteries; and improving the energy efficiency of aircraft and their engines. In 2025-2035, new technological solutions are expected to be actively implemented: after 2030, domestic flights will be powered mainly by biofuels; research on the use of hydrogen in aviation will continue. In 2035-2045, the main investments will be made in electrification and the development of hydrogen technologies: airport infrastructure will be adjusted for aircraft powered by different fuel types, and electricity-powered long-haul airliners will be developed. After 2045, no flights departing from Swedish airports will use fossil fuels, while new technologies will help achieve net zero flights.

Mexico

Rocha-Lona (2019) addressed the use of biofuels in the Mexican aerospace sector. The main research method was bibliometric analysis. The transport sector is the largest final energy consumer in Mexico and the aviation segment is the second largest energy consumer among all transport modes. At the end of 2014, fossil fuels were the main, and common, energy source for the transport sector, indicating the latter's dependence on them. However, given the combined effect of rising oil prices and concerns about environmental degradation and high carbon emissions, the

Mexican aerospace industry began to focus on developing biofuels as an alternative to conventional fossil fuels.

By 2030, the share of renewable energy sources in Mexico's total energy generation is expected to reach at least 20%. Mexico is also the third largest country in Latin America and the Caribbean in terms of arable land acreage (after Brazil and Argentina), which could significantly increase the share of biomass in its energy generation. Mexico's priority crops for aviation fuel production are jatropha, which has great potential because it can grow in adverse climatic conditions and with very little soil nutrients; sunflower, whose production costs are still high, though efforts are being made to reduce them; rapeseed, which has a high oil content for biofuel production and relatively low production costs; and oil palm, with low production costs and high agricultural performance. In the coming years, Mexico is expected to increase the production of all these crops, despite the fact that production-, supply chain- and regulation-related issues still remain, including those related to land use.

Brazil

A study focused on building roadmaps for biofuel application in the Brazilian aviation sector was published as early as in 2014 (Boeing, Embraer, Unicamp, Fapesp, 2014). In 2022, a study was publishedanalyzing the use of biomass to produce aviation biofuels (Escalante et al., 2022). The Brazilian aviation sector aims to reduce greenhouse gas emissions by up to 37% by 2030, and by up to 43% by 2050 (compared to 2005), in particular through the use of alternative fuels. Biomass has the greatest potential for full-scale application in the Brazilian aviation sector. Renewable sources in the Brazilian energy sector account for 42%, which is 13 percentage points higher than the world average. Currently, the use of biofuel in the country's aviation sector is less competitive than fossil fuels. At this stage, the main crops Brazil uses to produce biofuels are jatropha, soybeans, and sugar cane. There are also several promising sources more expensive to process, but often easier to obtain, including sunflower, peanuts, camelina, castor beans, oil palm, macauba, municipal solid waste, and used vegetable oil.

5. Discussion

The strategic documents of the countries under consideration include an agenda to reduce carbon dioxide emissions by transferring the aviation sector to alternative fuels (mainly passenger traffic). The programs offer sponsorship and support for developers and producers of SAF (for example, in the USA). Looking ahead to 2030, predictions include shortages in alternative fuel production or difficulties adapting aviation infrastructure. In this regard, a gradual transition to alternative fuel in aviation is planned by combining it with traditional types. According to analyzed documents, the most promising types of SAF are biofuels (IRENA, 2021a; KPMG, 2022) and synthetic kerosene (Sustainable Aviation, 2020; KPMG, 2022). In medium-term forecasts (up to 2030-2035), there are restrictions on the concentration of SAF in the fuel used (as a result of combining it with traditional fuel), and on flight range. Hydrogen and electricity as aviation fuel are currently being studied only in terms of long-term industry prospects. However, complete transition to SAF turns out to be impossible even in the long term.The aviation industry is likely to continue to have a negative impact on the environment even in the long term.

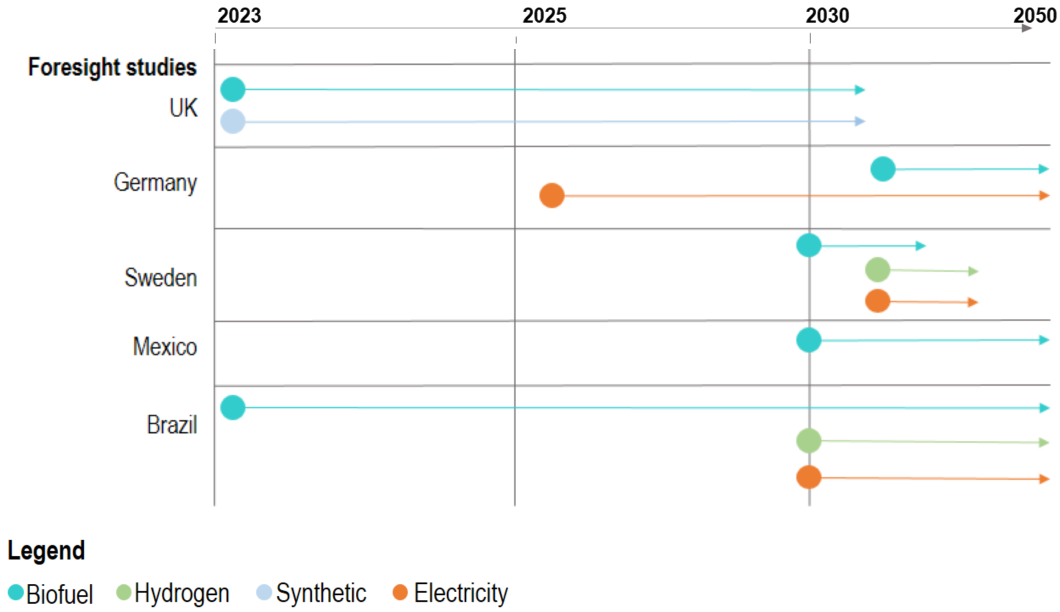

Figure 3. Analysis of Alternative Fuels' Application Prospects as Described in Various Documents

Note: Prepared by the authors.

Based on a comparative analysis of government, industry, and corporate documents and foresight studies, Figure 3 presents the development prospects for biofuels, synthetic fuels, hydrogen, and electricity in line with forecast periods the aviation industry uses.

Our study assesses the prospects for several clean aviation fuels from a global perspective. To date, the prospects for using sustainable aviation fuel in the short, medium and long term have not yet been studied. Key aviation fuel market players and aviation companies can take these results into account for further development and strategic planning.

6. Conclusions

In the course of testing the research hypotheses, the development prospects for alternative aviation fuel types were revealed. The authors came to the conclusion that countries that hold leading positions inthe aviation marketswill continue the gradual transition to sustainable fuels. Despite the active discussion of this topic, a full-scale transition will not be possible either in the short or medium terms. The reason is a set of factors, the main ones among them being the low level of technology readiness, the lack of resources, high costs, and the insufficient supply of sustainable fuels, plus the need to modify aircraft design and aviation infrastructure.Thus, the Hypothesis 1 is confirmed: Sustainable fuels can only be fully applied in the aviation sector in the long term.

Despite the fact that bio- and synthetic fuels are seen as the most promising sustainable fuel types in the medium term, their full-scale application hardly seems to be possible without blending them with hydrocarbon fuels. The reasons behind this are similar to those impeding a full transition to sustainable fuels: costs and levels of production output. Thus, the Hypothesis 2 is confirmed: In the medium term, bio- and synthetic fuels will be actively applied, but only as "additives" to conventional fuels.It is possible that in the future fuel production can be significantly increased due to the use of algae biomass, but it is difficult to estimate the growth rate of supply in the medium term given the different climatic and investment potentials of various regions. Other fundamental, and still open, questions are the expansion of green energy generation and carbon capture practices, which also require major investment and the implementation of green policies by most countries.

By the middle of this century, it may be possible to power aircraft not only with biofuels and synthetic kerosene, but with other energy sources such as hydrogen or electricity. Hypothesis 3 is also confirmed: Until the middle of the century, hydrogen and electricity will not be applied in commercial aviation at all, or their application will be very limited.By that time, relevant technologies should be developed and the production of next-generation aircraft might begin. It will also require adapting airport infrastructure and building fuel supply chains. Of particular importance seems to be increasing green energy generation. This factor can accelerate the introduction of such aircraft.

As directions for further research, we propose the development of technologies for the production of green energy and carbon dioxide capture, the analysis of technological capabilities and availability of resources for this. In addition, a promising area of research is a detailed assessment of the economic and environmental benefits of using alternative fuels, as well as the study of social and political factors that may influence the transition to new types of fuel. In addition, future research could focus on developing new technologies to produce more efficient and cleaner fuels, as well as creating more efficient infrastructure for their distribution and use.

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Declarations of interest

None

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