Environ Res Tec, Vol. 8, Issue. 4, pp. 1035-1049, December 2025

Environmental Research and Technology
https://dergipark.org.tr/en/pub/ert
DOI: https://doi.org/10.35208/ert.1531974

Review Article

Sustainable aviation fuels: Evaluating environmental and operational impacts

Caner İLHAN [1*]

[1]*Özyeğin University, Faculty of Aviation and Aeronautical Sciences, Department of Professional Flight, Istanbul, Turkiye*

ARTICLE INFO

Article history
Received: 12 August 2024
Revised: 05 November 2024
Accepted: 01 January 2025

Key words:
Aviation, CO_2 emission, hydrogen, SAF, sustainable fuels

ABSTRACT

Between 2013 and 2018, commercial aviation saw a 70% increase in carbon dioxide (CO_2) emissions, significantly outpacing United Nations projections. This alarming trend is anticipated to continue, with emissions potentially tripling by 2050, driven by economic expansion and an increasing dependence on fossil fuels. In 2022, the aviation industry's energy consumption reached 12.1 MJ/RTK, with projections forecasting a 2.8 to 3.9-fold increase by 2040. Without a strategic shift towards sustainable alternatives, aviation emissions are expected to reach 2,000 megatons by mid-century, posing a severe threat to global climate stability. This study emphasizes the urgent need for the aviation sector to adopt high-energy, reliable alternative fuels that can mitigate its environmental impact. A comprehensive evaluation and comparison of potential alternative fuels are presented, focusing on their energy densities, production processes, and ecological footprints. The research highlights the potential of these alternatives to meet the industry's energy demands while significantly reducing greenhouse gas emissions. Technological advancements in fuel production and aircraft propulsion are also explored, underscoring their role in achieving meaningful emissions reductions. The study argues that integrating sustainable practices and fostering innovation within the aviation sector is critical for ensuring long-term sustainability and resilience. By transitioning to alternative fuels and embracing new technologies, the aviation industry can address its environmental challenges and lead the way in global efforts to combat climate change and achieve net-zero emissions by 2050.

Cite this article as: İlhan C. Sustainable aviation fuels: Evaluating environmental and operational impacts. Environ Res Tec 2025;8(4) 1035-1049.

INTRODUCTION

Carbon dioxide (CO_2) emissions from commercial aviation climbed 70% faster than the UN forecasts between 2013 and 2018 and are anticipated to triple by 2050, accounting for a fifth of all industries [1]. Taking into account that a region is growing economically, it is assumed that the demand for air travel for that region also increases [2]. In addition, population growth, digitalization, industrialization, and the continuous increase in international trade opportunities have caused an increase in the aviation sector. With this fast increase in this industry and technological development, the energy required grows daily. This required energy is fulfilled mainly by fossil fuels or their derivatives, resulting in greenhouse gas emissions, one of the predecessors of the climate crisis, one of the age's largest and most popular crises. When energy consumption in aviation is considered, commercial passenger aircraft will utilize 12.1 MJ/RTK energy in 2022 [3]. Fuel consumption in aviation is anticipated to increase by 2.8 to 3.9 times by 2040 as worldwide flight traffic density rises [4].

Considering advancements in aviation and increasing ener-

***Corresponding author.**
*E-mail address: caner.ilhan@ozyegin.edu.tr

gy supply, CO_2 emissions will rise if fossil fuel consumption continues. According to [5], by 2050, Aviation emissions are expected to cause 2,000 megatons of carbon dioxide emissions, and more than 620 Mt of fuel will be needed to carry out this activity. As a result, the aviation industry, like all other sectors, will have to transition to sustainable fuel alternatives.

Efforts are being undertaken to prevent environmental pollution and address the energy crisis using renewable energy supplies. Given current circumstances, various investigations are being conducted on using sustainable fuel alternatives as an energy source.

Within the scope of this research, considering that the aviation sector is a sub-branch of the transportation sector, it would be appropriate to make an introduction by evaluating the fuel type for the transportation sector. Petroleum-based liquid fuels are used in the transportation sector. When the use of this type of fuel is examined as a percentage, the transportation sector has a share of 54% [6]. The use of petroleum-derived fuels in the transportation sector is increasing due to the rapid growth of this sector and is projected to grow by 1.3% every year until 2030 [7].

As a result of the production of these fuels and their subsequent use to obtain energy, air pollutants are released. These substances depend on the chemical structure of the fuel and generally contain carbon-containing gas molecules. Pollutants are formed due to these fossil fuels [8]. When we think about emissions from aviation, emissions from these vehicles increase even faster as the number of aircraft continues to grow. Due to the increasing energy demand in the aviation sector along with the continuous investments and innovations made by developed and developing countries in the aviation sector, the concept of sustainability has gained importance for the protection of climate and environment in the aviation sector [9]. In this context, studies should be carried out in the aviation sector to bring it together with sustainable fuels and energy sources, like other vehicles belonging to the transportation sector.

Many proposals have been developed to reduce these emissions. With the development of technology day by day, it has been ensured that emissions are significantly reduced with engine designs with increased efficiency and the determination of sustainable fuels and the determination of suitable fuel alternatives [10].

When evaluating fuel alternatives for aircraft, choosing fuels with high energy content is imperative. One of the main reasons why alternatives have been complex to find so far is that fuel alternatives with the amount of energy required by aircraft cause problems in onboard applications [11].

Choosing suitable fuels with high energy content is imperative when evaluating fuel alternatives for aircraft. The research recognizes the significance of aligning fuel alternatives with the type of engine available for aircraft. Once appropriate fuels are identified, rigorous testing and studies are essential to ascertain their reliability [7]. This research aims to compare the properties of alternative fuels that can be used in aviation and to determine the appropriate ones.

In conclusion, the research aims to comprehensively analyze alternative fuels for aviation, comparing their properties and determining the most suitable options. By addressing the current challenges, emphasizing the importance of sustainability, and advocating for thorough testing, the research contributes to the broader discourse on mitigating the environmental impact of the aviation sector.

FUEL ALTERNATIVES

When evaluating fuel alternatives, the most important expectation is that the raw material is readily available and sustainable. Based on these expectations, suitable fuel alternatives are sought for gasoline and diesel engines, which are still out of effect and are sought as alternatives. In this direction, many options are encountered when fuel alternatives that can be used in aviation are evaluated. Therefore, it is essential to determine these alternatives well and to use the appropriate fuel in line with the target.

As the aviation industry seeks to reduce its carbon footprint and meet global sustainability targets, exploring alternative fuels has emerged as a critical area of focus. Traditional jet fuels, derived from fossil sources, are significant contributors to greenhouse gas emissions, driving the urgent need for greener alternatives. This section will explore the various sustainable fuel alternatives currently under consideration, evaluating their potential to transform aviation into a more environmentally friendly sector. These alternatives, ranging from biofuels to synthetic fuels, offer varying degrees of sustainability, feasibility, and technological readiness, each with advantages and challenges. Examining these options aims to provide a comprehensive understanding of the role these fuels could play in shaping the future of aviation.

As sen in Figure 1, the share of aviation in oil consumption in 2019 is substantial. Considering both the growth rate and the fuel consumption rate in aviation, a transition to alternative sources will significantly impact the aviation sector, which has a share of 8.6% in the use of 169 EJ of oil to prevent carbon emissions.

Biofuels

When an examination is explicitly made for sustainable aviation fuels, aviation-based biofuels stand out as the most dominant fuel alternative among existing fuel systems due to their maturity level and applicability [13]. Many different production methods can produce aviation biofuels. The preference for other production methods for different feedstocks creates a necessity depending on the physical and chemical structure of the product to be used [14].

As illustrated in Figure 2, which presents a diagram of bio jet fuel pathways, biofuels have emerged as a promising alternative to conventional jet fuels, mainly due to their potential to reduce greenhouse gas (GHG) emissions significantly, and there are several ways to produce renewable jet fuel with bio-sources. Two prominent methods for producing biofu-

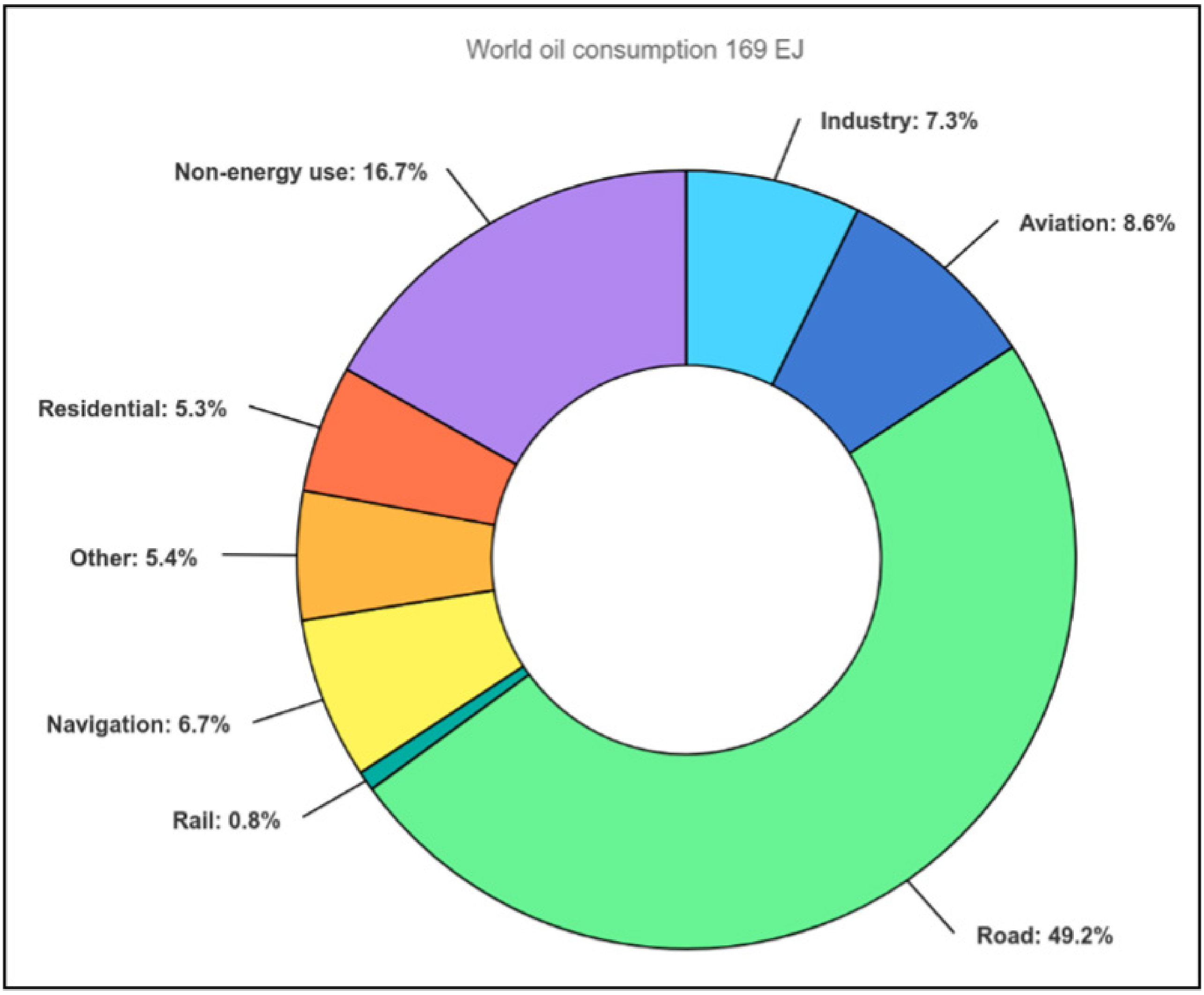

Figure 1. Share of oil final consumption by sector, 2019 [12]

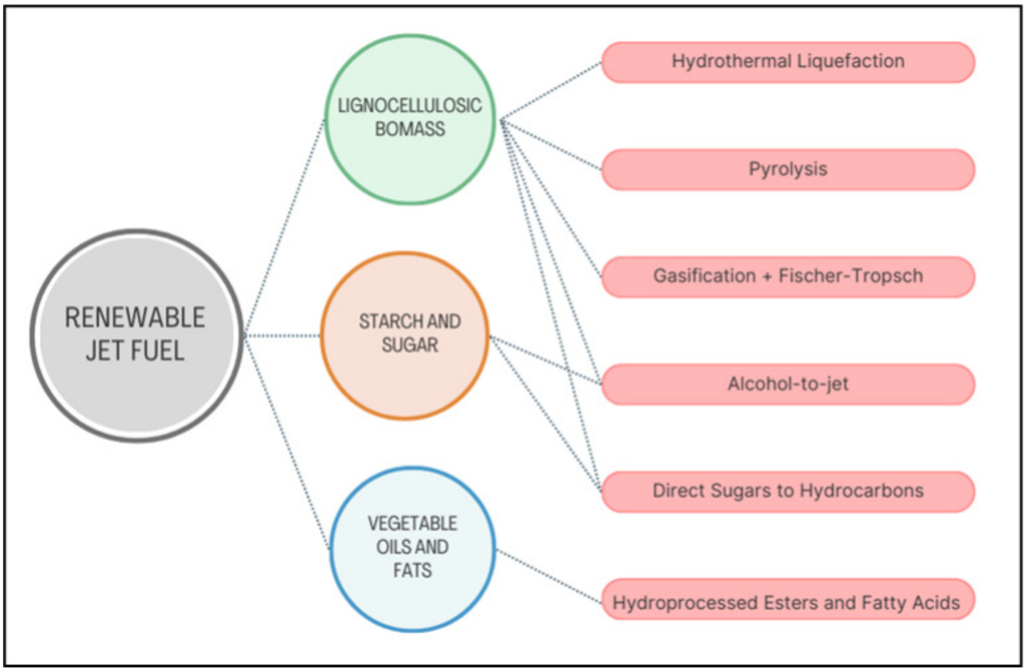

Figure 2. Diagram of bio jet fuel pathways [14]

els, the Fischer-Tropsch process and the Hydroprocessed Esters and Fatty Acids (HEFA) process, have been extensively studied. These methods have shown considerable promise, with research indicating a marked reduction in GHG emissions compared to traditional petroleum-derived jet fuels. This reduction is crucial for the aviation industry, which is under increasing pressure to meet global sustainability targets and reduce its environmental footprint [15]. When the feedstocks of biofuels that can be used in aviation are examined, it can be seen that it is possible to obtain biofuels from different types of plant derivatives.

When delving into the feedstocks used for biofuel production, it becomes evident that various plant derivatives can be harnessed for this purpose. These feedstocks vary greatly depending on regional agricultural practices and the availability of raw materials. Among these, sugar cane stands out as a significant crop for biofuel production. A substantial portion of biofuel production globally is derived from sugar cane, with Brazil leading the charge. Brazil's dominance in this sector is closely linked to its vast sugarcane plantations, which benefit from the country's tropical climate. Sugar cane is one of the most photosynthetically efficient crops. Still, it also has the advantage of thriving in regions that may not be suitable for other types of agriculture, further enhancing its appeal as a biofuel feedstock [16].

In addition to Brazil's contributions, the United States has established itself as a global leader in the use and production of biofuels. The U.S. primarily focuses on converting corn, grain, and starch into biofuels, with maize playing a central role. Maize, particularly maize grain, is the cornerstone of the U.S. biofuel industry, accounting for more than 54% of the global ethanol market. The U.S. has heavily invested in the infrastructure and technology needed to efficiently convert these feedstocks into biofuels, positioning the country as a critical player in the biofuel market. This focus on maize-derived ethanol not only supports the country's energy independence goals but also contributes to global efforts to reduce reliance on fossil fuels [17].

Beyond these dominant crops, there is ongoing research into other potential feedstocks that could further diversify the sources of biofuels. For instance, oilseeds, algae, and even waste products are being explored for their viability in biofuel production. Each of these feedstocks presents its own set of advantages and challenges, from the efficiency of conversion processes to the sustainability of large-scale cultivation. As the demand for sustainable aviation fuels continues to grow, exploring and optimizing these alternative feedstocks will be crucial in ensuring a reliable and environmentally friendly supply of biofuels for the aviation industry.

When the situation of biofuels in the world is examined and research is conducted on the amount required to decarbonize aviation, according to the International Energy Agency, approximately 220 million tons/year of biofuel is needed to decarbonize the aviation sector completely [18]. Based on this situation, when the current situation and targets in the use of biofuels are examined, it is pointed out that according to ICAO, SAF is distributed at approximately 57 airports around the world, and more than 440,000 commercial flight activities are carried out from these airports [19].

Although biofuels are planned to be gradually introduced on international flights, it is aimed to replace 2% of fossil fuels by 2025, followed by 5% in 2030 and 63% in 2050 [20]. As a result of these changes, it is expected that 90% of conventional aviation fuels will be replaced with biofuels, reducing emissions from aviation by 53% by 2050 [5, 21].

In addition to the advantages of using biofuels as fuel, evaluating the process of becoming a fuel in terms of sustainability is beneficial. First of all, if we look at economic sustainability, The financial viability of biofuels depends on their competitiveness with fossil fuels. Sources state that the development of next-generation biofuel technologies in commercially large-scale production facilities has been slow due to financial, legal, scale-up, technological inefficiencies, and regulatory barriers [22, 23]. The most basic cost that can be evaluated in economic sustainability is the cost of raw materials. The cost of raw materials can account for about 80% of the cost of biofuel production [24, 25]. It is envisaged that raw waste materials such as edible oil will be used to produce biofuels, reducing production costs.

Another aspect that contributes significantly to the economic viability of biofuels is their capital cost. CAPEX, which can account for 15% of the total cost in traditional processes, can go up to 30% in biofuel production routes [26]. It is the result of using a new technology that significantly increases biofuel production's high operating and capital costs; energy efficiency has not yet been fully achieved, and thus, the process economy.

When evaluated in terms of environmental sustainability, it means reducing greenhouse gas emissions and minimizing other environmental impacts throughout the life cycle of biofuels [27]. First-generation biofuels (e.g., biodiesel) can compete with the food supply and lead to deforestation. Second-generation biofuels (e.g., lignocellulosic biofuels) have the potential to mitigate these problems [28]. Life Cycle Analysis (LCA) is an essential tool for assessing the environmental impact of biofuels. LCA studies have shown that biofuels can significantly reduce greenhouse gas emissions compared to fossil fuels [29, 30]. When the literature is examined, it emphasizes that the LCA methodology should be used with a forward-looking perspective to evaluate the future potential of biofuel production. This approach takes into account expected constraints on emission levels, as well as market volatility, economic fluctuations, consumer Demand, and other possible events that could significantly affect the development of technology [31, 32].

In conclusion, it can be said that biofuels have the potential to reduce reliance on fossil fuels and create a more sustainable transportation system in the long term, especially for the aviation sector. However, for biofuels to be genuinely sustainable, their economic, environmental, and social impacts must be considered and supported by the joint efforts of policymakers, researchers, and industry.

Electrofuels

When the energy source of the future is examined, it is envisaged that electrical energy will be used in a significant way in the sustainable vehicles of the future, including the renewable energy alternative that can be converted from fossil fuels and aviation. However, one of the factors limiting the use of electrical energy in transportation can be seen as the inability of energy storage capacities to provide sufficient capacity considering today's technology. Although the developments in the context of technological developments and new materials used are too many to be assimilated, the desired energy levels have not been reached due to physical limitations [33].

After evaluating the potential of using electrical energy, it is possible to reach this energy with minimum loss and use it in its content by electrolysis or electrosynthesis. As a result, it is possible to call all kinds of fuels produced with the "power-to-gas" or "power-to-liquid" approach as electric fuels [34].

There are different approaches to producing electrofuel. As a result, the type of fuel produced may also vary. Hydrogen is a substance with a high energy density. However, since its production and subsequent transportation are complex, different electrofuel approaches gain importance.

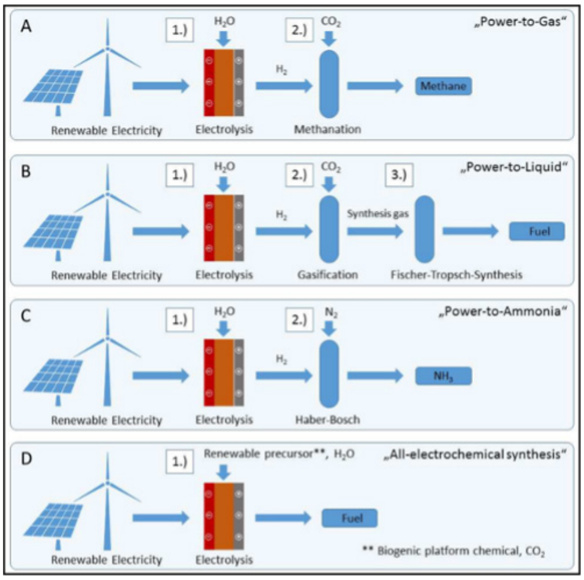

Figure 3. Illustration of electro fuel generation [34]

The electro fuel production approaches shown in Figure 3, [34] summarize very well. The use of renewable energy for electrolysis is every day for each approach. Afterward, there are differences in the product produced according to the applied process. The process shown in Fig. 3A is a power-to-gas process of methanezing hydrogen under carbon dioxide. The exothermic Sabatier process is used: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$. The transportation of this produced methane is much easier than hydrogen transportation.

The significance of electrofuels becomes even more pronounced when considering their potential to integrate renewable energy sources directly into fuel production. As global energy systems transition towards cleaner sources, the ability to convert surplus renewable electricity into storable and transportable fuels addresses one of the critical challenges of renewable energy: intermittency. Electrofuels can act as a bridge between renewable energy generation and the steady fuel supply needed for continuous aviation operations by utilizing excess electricity generated during periods of low demand.

Moreover, the versatility of electrofuels is further highlighted by the variety of end products they can yield. For instance, methane is a commonly discussed product due to its more accessible transportation than hydrogen; other electrofuels like methanol and synthetic kerosene are also gaining attention. These fuels can be used directly in existing aircraft engines with little or no modification. This is a significant advantage in the aviation industry, where the infrastructure and fleet turnover can be slow and costly [35].

In the context of sustainability, electrofuels offer a promising route to achieving carbon-neutral or even carbon-negative aviation. By combining renewable energy with carbon capture and utilization (CCU) technologies, electrofuels can potentially neutralize or offset the carbon emissions associated with their production and use [34]. This capability is significant for the aviation sector, which faces considerable challenges in reducing its carbon footprint due to the high energy density required for long-haul flights [13].

The ongoing research and development in electrofuel technologies are expected to improve efficiency and cost-effectiveness. Innovations in electrolysis processes, catalysts, and carbon capture techniques are vital areas where advancements could make electrofuels more competitive with conventional jet fuels. Additionally, the scalability of electrofuel production is being explored, with pilot projects and demonstration plants being established worldwide to validate these fuels' commercial viability.

As the aviation industry continues to seek sustainable fuel alternatives, electrofuels stand out as a promising option, combining renewable energy's benefits with the practicality of liquid fuels. The continued development and integration of electrofuels into the global energy system will be crucial for meeting the aviation sector's long-term sustainability goals and reducing its environmental impact.

When electrofuels are produced using electricity from renewable energy sources, they can significantly reduce net carbon emissions throughout their life cycle. This is critical to reducing the aviation sector's impact on climate change [36]. The amount of electrical energy required for the production of electrofuels can vary depending on the technologies used and the production process [13].

The production cost of electrofuels is currently significantly higher than that of conventional fossil jet fuels [37, 38]. This poses a significant obstacle to the widespread adoption of electrofuels. In addition, the need for large-scale electrofuel production facilities to meet the fuel demand of the aviation industry makes it challenging to use this fuel.

Battery

Battery-based power generation can be used in aviation both to generate thrust and to provide non-propulsion energy.

Battery usage architecture can be explained with different approaches. These It can be called More Electric, Hybrid Electric, or Fully Electric [13]

Although batteries have been used in airplanes for years, the use of the fully electrically powered system approach in airplanes is still considered at the initial stage in today's conditions. The reason for this is that today's battery technology is not at the desired power and energy levels (specific to aircraft). Battery use is limited in aircraft in the long-haul aircraft segment, especially due to the fact that the desired power levels in civil aviation are very large [39].

There are several approaches to studying the use of batteries to generate thrust in airplanes. In terms of efficiency and enthusiasm for all-electric aircraft, it is possible to use the battery, especially in UAV approaches.

When an evaluation is made for commercial aircraft, it is possible to fly at very short ranges under today's technology. This is an option that can be considered for training planes and air taxis with low passenger capacity. Commercial transport requires batteries with a very high energy capacity, depending on the very large passenger and load. This is not possible in today's conditions.

There are some significant obstacles to the proliferation of all-electric aircraft. The biggest obstacle is that the energy density of batteries is still low compared to conventional jet fuels. This limits the range and carrying capacity of the aircraft [13].

Figure 4 shows why battery-powered transport is a challenge for commercial air transport. Even with generous estimates about aerodynamic and propulsive efficiency, structural weight, and needed reserves, the 19-passenger DHC-6-400 Twin Otter requires a specific energy exceeding 300 W-hr/kg.

The limitations of current battery technology in aviation are primarily rooted in energy density and weight challenges. While batteries have made significant strides in energy storage capabilities over the past few decades, they still fall short when meeting commercial aviation demands. The energy density of even the most advanced lithium-ion batteries is far lower than that of traditional jet fuels, which limits their practicality for powering large, long-haul aircraft. This gap in energy density means that, for the foreseeable future, fully electric commercial aircraft will likely be confined to short-haul flights or specialized applications such as training aircraft and urban air mobility solutions, like air taxis.

Hybrid-electric systems present a more viable solution for reducing emissions and fuel consumption in larger aircraft. These systems combine conventional jet engines with electric propulsion, allowing for more efficient fuel use and reduced emissions, particularly during takeoff and landing, where fuel consumption is highest. Hybrid-electric aircraft can leverage the strengths of both battery power and traditional fuel, enabling longer range and greater payload capacities than fully electric systems alone. This approach not only enhances the overall efficiency of the aircraft but also serves as a critical step toward the gradual integration of more sustainable technologies into the aviation industry.

Moreover, ongoing research into advanced battery technologies, such as solid-state batteries, promises to further improve the energy density and safety of batteries used in aviation. Solid-state batteries, which replace the liquid electrolyte found in conventional lithium-ion batteries with a solid electrolyte, have the potential to store more energy and reduce the risk of thermal runaway, a critical safety concern in aerospace applications. If these technologies can be scaled and commercialized, they may pave the way for more widespread adoption of electric propulsion in larger aircraft.

While fully electric commercial aircraft remain a distant goal, the continued development of battery technology and hybrid-electric systems represents a crucial pathway toward a more sustainable aviation future. As battery technology advances, we can expect to see incremental improvements in the range and capacity of electric and hybrid-electric aircraft, bringing the industry closer to achieving its long-term sustainability objectives.

One of the important developments that paved the way for the use of batteries to become more frequent is that with a hybrid design, the battery can be seen as an important source behind the fact that it can be seen as an energy source in the aviation industry. Hybrid electric aircraft use both batteries and conventional jet engines. This system was developed to alleviate the energy density problem of batteries and to provide a solution for long-range flights.

As mentioned earlier, lithium-ion batteries have a higher energy density than other batteries, but the energy density of around 300-400 Wh/kg is much lower than the energy density of jet fuel, which is about 12,000 Wh/kg [40]. This creates a barrier to an all-electric approach with batteries in aircraft.

Based on these approaches, batteries have a significant potential for the decarbonization of the aviation industry. It is possible to say that fully electric and hybrid electric aircraft are some of the promising technologies to reduce fossil fuel consumption and emissions. Even if battery technologies in today's conditions are not suitable for this at the moment, it will be possible for battery aircraft to become more common in the future by providing continuous developments in technology and improvements in issues such as energy density, cost, and life.

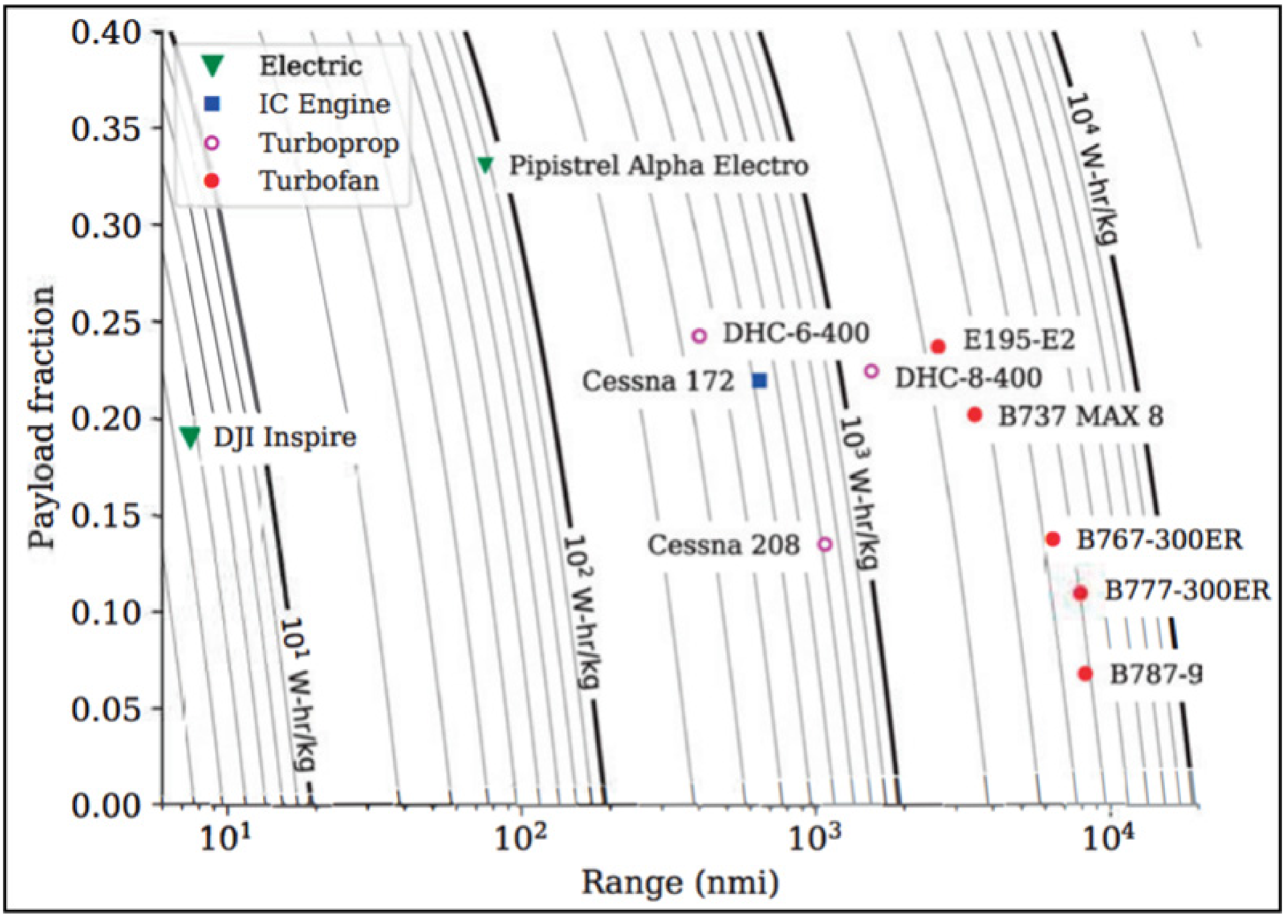

Figure 4. Battery-specific energy needed for a certain payload fraction and range

Hydrogen

Utilizing hydrogen as a fuel, particularly in a hybrid-electric drive train configuration comprising a fuel cell and a battery, represents a promising approach for short and intermediate-distance flights. This approach has the potential to decrease the climate impact of such flights by up to 90% [41].

In addition, how hydrogen is used in aircraft propulsion is also important in terms of emission emissions. Direct combustion of hydrogen to generate propulsion or electric propulsion generation with the use of fuel cells are among the options that can be used [42].

When propulsion is produced by burning hydrogen in a modified engine similar to conventional jet fuel, emissions of CO_2, CO, SOx, and other harmful gases are significantly reduced, although NOx and water vapor are still emitted.

Two different combustor designs are under investigation for NOx reduction: Lean Direct Injection (LDI) and Micro-Mix Combustors (MMC) [43, 44]. In both methods, the NOx gas released is at lower levels. Contrail is present because water vapor is another gas that causes emissions when hydrogen is burned. This contrail still causes the formation of a greenhouse effect. In the formation of the contrail, there is the following situation: it remains in the air more due to the particles in the contrail formed as a result of kerosene-derived fuels. With the use of hydrogen as a fuel, this nucleation is significantly reduced [45].

Considering the situation in which hydrogen is produced in aircraft through the fuel cell, it creates a clear solution for "net-zero" in terms of GHG. This "net-zero" prevents all emission gases such as CO_2 , NOx, SOx, CO, and HC. However, water vapor production is also available in this type of propulsion production [46].

As a result of the reactions on the anode and cathode surfaces in the fuel cell, the net reaction equation is $2H_2 + O_2 \rightarrow 2H_2O$ + electrical energy [47]. As can be understood from the overall reaction, there is no by-product other than water and electrical energy. In this way, if the contrail is overcome, "net zero" is achieved under all conditions [48].

When two alternative hydrogen propulsion generating methods are examined, it is claimed that fuel cells provide more efficiency. It has been determined that using fuel cells requires 20-40 percent less hydrogen. When compared mathematically, there is a combination of 55% average fuel cell efficiency, 90% powertrain efficiency, and 40% average hydrogen burning efficiency. Furthermore, using electrical impulses improves energy distribution. This method also allows for fuel savings [41].

The potential of hydrogen as a sustainable aviation fuel is not limited to short and intermediate distances. There is growing interest in exploring its application for long-haul flights as well, though this presents additional challenges. For long-haul flights, the main concern is the storage and transportation of hydrogen, which, due to its low energy density per volume, requires significant tank space and advanced insulation techniques to maintain it in liquid form [49]. Researchers are investigating innovative storage solutions, such as cryogenic tanks and advanced composite materials, to address these challenges. These technologies are crucial to enabling the use of hydrogen on longer flights without compromising the aircraft's payload capacity or range.

Another important consideration is the infrastructure required for hydrogen production, storage, and distribution. Currently, the global hydrogen supply chain is still in its infancy, with most hydrogen being produced using fossil fuels, which negates some of the environmental benefits of using hydrogen in aviation. However, advancements in green hydrogen production—using electrolysis powered by renewable energy—are essential to ensuring that hydrogen-powered aviation truly contributes to the reduction of global greenhouse gas emissions [49]. Developing a robust infrastructure for green hydrogen will be critical for scaling up its use in the aviation sector.

In addition to the technical and infrastructure challenges, the economic viability of hydrogen as a fuel must also be addressed. The cost of producing, storing, and transporting hydrogen is currently higher than that of conventional jet fuels. However, as the technology matures and economies of scale are realized, these costs are expected to decrease. Government policies and incentives, such as carbon pricing and subsidies for renewable energy, will also play a crucial role in making hydrogen a competitive option for aviation.

The environmental benefits of hydrogen are clear, but the transition to hydrogen-powered aviation will require coordinated efforts across the industry, governments, and research institutions. Collaborative projects and public-private partnerships are already underway, with several leading aerospace companies and airlines investing in hydrogen technology and pilot projects. These initiatives are critical for demonstrating the feasibility of hydrogen as an aviation fuel and for building the necessary expertise and infrastructure to support its widespread adoption.

While significant hurdles exist, hydrogen represents one of the most promising pathways to achieving sustainable aviation. Whether used in direct combustion or fuel cells, hydrogen has the potential to reduce the aviation industry's carbon footprint drastically. As research and development continue, and as the necessary infrastructure and economic frameworks are put in place, hydrogen could play a pivotal role in the future of aviation, enabling cleaner, more sustainable air travel.

Speaking of the strengths and weaknesses of hydrogen, it is possible to understand it better by comparing it with conventional fuel. Table 1 shows the comparison of Hydrogen and Jet fuel in terms of different properties.

As can be seen from Table 1, hydrogen has an advantage over conventional jet fuel. The main reason behind this advantage is that it has a higher gravimetric energy density and provides a great advantage in CO_2 emissions. Again, from the same table, it can be seen that although the gravimetric energy density of hydrogen is high, its volumetric energy density is low compared to kerosene. Due to this low value, it will need more space in terms of volume. In this case, it can be said that the tank design requires significant activity in the case of the use of hydrogen.

Different storage methods are encountered when storing hydrogen for aviation use. The most well-known of these are pressurized gas storage, liquid hydrogen storage, and chemical storage. In the pressurized gas storage method, hydrogen is stored in gaseous form under high pressure and put into use. Although this storage method is one of the most preferred methods, it also brings the disadvantage that the tanks are bulkier and heavier [52]. In the liquid hydrogen storage method, which is the second method that allows hydrogen to be stored at cryogenic temperatures, the complexity and cost of the system prevent the preference of this method in today's conditions and provide a high energy density [53]. Given the potential of hydrogen in the aviation sector, it should be considered that its storage has additional challenges. Due to weight and volume constraints on aircraft, hydrogen must be stored efficiently and safely. Looking at the literature, it is stated that the use of liquid hydrogen for hydrogen storage in aviation is considered [54, 55].

Considering these situations, the advantage of the energy density of hydrogen, as well as the emergence of more efficient hydrogen tanks and storage methods, which are expected to emerge with developing technologies and research of new materials, allow hydrogen to become a more efficient, safe, and economical aviation fuel.

Table 1. Comparison of Hydrogen and Jet Fuel with different characteristics [49, 50, 51]

Property	Hydrogen	Jet Fuel
Gravimetric Energy Density (kWh/kg)	33.3	11.89
Volumetric Energy Density (kWh/m3)	2359	9637
CO_2 Emission (kg/GJ)	0	720
H_2O Emission (kg/GJ)	750	290

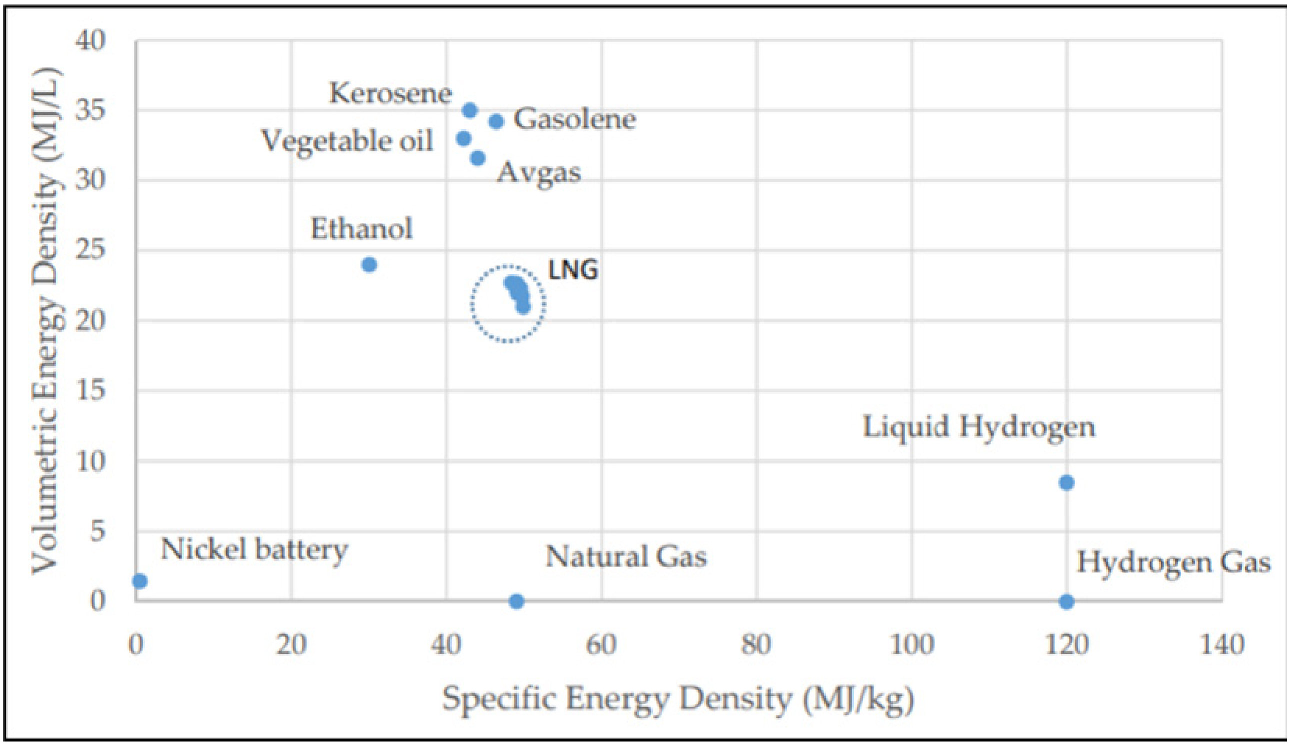

Figure 5. Fuel Energy Density comparison chart [57]

LNG

LNG, like liquefied biomethane, cryogenic fuels are considered among the alternative fuels due to their high specific energy density. However, when the volumetric properties of this type of fuel are evaluated, they are in a disadvantageous position compared to other fuel alternatives. The fuel alternatives shown in Figure 5 are shown as comparisons of different fuel options planned to be used in aviation in terms of energy density and volumetric density [56].

Kerosene, at the top of the chart, is an ideal fuel alternative in aviation due to its volumetric density. Other alternatives below it are fuels with high carbon content and are naturally available in liquid form.

Natural gas, predominantly composed of methane, has been suggested as a viable alternative aviation fuel due to reduced fuel tank weight and increased capacity facilitated by liquefaction. The pioneering use of liquid methane in aviation began with the Beech Sundowner in 1980. Subsequently, modified versions of the TU-154 and TU-155 successfully completed flights using liquefied natural gas (LNG).

The discovery and expansion of huge natural gas reserves through shale fracking resulted in a dramatic decline in natural gas prices, which reached their lowest level since 1995 in 2020. With a 16% greater heating value and a higher hydrogen-to-carbon ratio compared to Jet A, LNG emerges as a promising alternative aviation fuel. In this regard, LNG holds potential as a clean option, serving as a transitional step towards the advancement of net-zero carbon emission alternatives such as biomethane or hydrogen [56].

Although LNG is known to be a clean alternative, depending on the type of natural gas used, it cannot perform effectively in the aircraft due to the lower heating value and the density of the fuel. In addition, it will increase the cost due to the need for modification of the engine to use this fuel. In addition, although LNG causes less CO_2 emissions compared to kerosene-derived fuels, it cannot meet the targets in terms of achieving net-zero emissions. This causes the long-term goals not to be achieved.

If a general evaluation is to be made about LNG; It can be said that it has lower carbon emissions than jet fuels. When methane emissions from LNG are controlled, they can play an important role in reducing carbon emissions in aviation. In addition, LNG can provide good fuel economy due to its higher energy density, which can effectively reduce operational costs for airlines. In addition, thanks to the abundance of LNG worldwide, it plays an active role in increasing fuel supply security in the aviation sector.

In addition to these, it will be useful to mention the disadvantages to compare other fuels. LNG is complex and costly, as cryogenic temperatures are also required to transport and store. In addition, methane, the main component of LNG, is considered a potent greenhouse gas; Methane leaks during the production, distribution and use of LNG can have negative effects on climate change. Another situation that needs to be evaluated will be compatibility with existing technologies. The need to modify LNG to work with existing aircraft engines will bring with it technical challenges and additional costs.

Therefore, while LNG offers some emission advantages over traditional jet fuels such as kerosene, it can be described as less environmentally friendly than other alternatives. Overcoming challenges such as storage, infrastructure, methane emissions minimization and engine compatibility for widespread adoption of LNG will pave the way for the use of this fuel.

Ammonia

It is possible to evaluate ammonia as another fuel alternative. Ammonia is one of the important alternative solutions for decarbonization. Therefore, great studies are being carried out for the production of green ammonia [58]. Ammonia is a versatile fuel because it has a less complex storage option than hydrogen and has a high energy density.

Ammonia is a suitable fuel in that it can be used both directly as a fuel and as an alternative fuel by converting it to hydrogen [59]. The use of SOFC, which is a fuel alternative for the direct use of ammonia, is also one of the promising technologies for ammonia [60].

One of the biggest differences between hydrogen and ammonia is what form of substance it is in at high temperatures. When the performance characteristics of ammonia are evaluated, it can be understood that it is an effective fuel in many respects. It provides advantages not only for hydrogen production, but also in different areas such as internal cooling, turbine cooling, elimination of NOx gases.

Ammonia emerges as a promising alternative aircraft fuel when considered alongside sustainable aviation fuel (SAF) and hydrogen. It presents several advantages over hydrogen, including higher volumetric energy density, a more favorable flammability rating, and accessibility via existing supply chains. Despite its higher toxicity compared to hydrogen and SAF, valuable handling expertise can be drawn from the fertilizer and shipping industries. Moreover, ammonia's non-coking properties render it suitable as a heat sink for compressor intercooling. Instead of direct combustion, this paper advocates for catalytic cracking of ammonia into hydrogen. Performance data from an existing aircraft engine for a modern narrowbody aircraft were adjusted to accommodate the novel fuel concept, and an intercooler was dimensioned based on anticipated operating conditions both on the ground and during flight [61].

Solar Cells

As a massive energy source, the sun offers immense potential for harnessing sustainable power. Solar cells can convert this energy into electricity, providing a clean and renewable power source. In aviation, leveraging solar energy presents a compelling opportunity to reduce emissions and improve sustainability. However, the current technological landscape poses certain limitations.

According to the efficiency chart published by the National Renewable Energy Laboratory [62], the conversion efficiency of solar cells, which are crucial in transforming solar energy into electrical energy, ranges between 30-40%. This figure represents the maximum achievable efficiency under ideal conditions. However, additional efficiency losses occur when integrated into aircraft systems due to the inherent inefficiencies in various subsystems, such as energy storage, power management, and distribution. These losses further reduce the net efficiency of the overall system, making it challenging to achieve high power outputs.

Given the current technological constraints, the electrical energy generated and stored through solar cells is primarily suitable for powering aircraft in the Unmanned Aerial Vehicle (UAV) segment. With their relatively lower power requirements, UAVs can benefit from solar energy, enabling longer flight durations and reducing reliance on conventional fuels. The net-zero emission nature of solar energy, which involves no combustion of fossil fuels, aligns with global sustainability goals, particularly in reducing the aviation industry's carbon footprint [63].

However, several drawbacks must be addressed. Weather conditions, notably cloud cover, significantly impact the efficiency of solar cells. On cloudy days or during nighttime, solar energy generation is severely limited, necessitating reliance on energy storage systems, such as batteries. This reliance introduces additional challenges, as batteries are subject to the limitations outlined in Section 2.3, including energy density, weight, and charging times. Furthermore, the integration of solar cells into aircraft structures, such as wings or fuselage, must be carefully designed to avoid aerodynamic penalties that could negate the benefits of solar energy.

Despite these challenges, ongoing research and development efforts aim to improve the efficiency of solar cells, enhance energy storage solutions, and optimize the integration of solar technology into aircraft. Advances in materials science, such as the development of lightweight and flexible solar panels, could potentially expand the applicability of solar cells to larger aircraft segments in the future [64]. Additionally, innovations in energy management systems may mitigate some of the current limitations, allowing for more effective utilization of solar energy in aviation.

In conclusion, while solar cell systems are currently limited to small segment aircraft, particularly UAVs, their potential to provide supplementary power and reduce emissions is significant. As technology evolves, solar energy could play a more prominent role in sustainable aviation, contributing to the industry's transition towards cleaner and more efficient power sources.

RESULT AND DISCUSSION

While electrical and chemical storage methods are viable for generating propellant power in aviation, the stringent thrust-to-weight ratios necessitate restricting the use of electrical batteries to smaller aircraft and shorter flights. Preliminary assessments suggest that in order to realize widespread zero-emission commercial aviation by the 2050s, e-H_2 demonstrates superior performance metrics across a range of mission flight profiles compared to other fuel options that have been evaluated [65, 66].

Hydrogen offers an unparalleled gravimetric energy density of 120 MJ/kg, which notably exceeds the 43-36 MJ/kg range of kerosene [61]. However, the storage of liquid hydrogen introduces complexities, as its volumetric energy density of 8.5 GH/m³ is notably lower than the 35-38 GJ/m³ range for kerosene [67]. Due to its low volumetric energy density, hydrogen requires storage either as a cryogenic liquid at 20 K (-253 °C) or as a gas at high pressure (approximately 700 bar). However, both of these on-board hydrogen storage methods pose challenges for the commercial air transportation industry, potentially adding weight to an airplane and thereby restricting its range or passenger capacity [51].

Cryogenic storage methods also need to address thermal shock during refueling to maintain the durability of the fuel system. Moreover, the elevated flame temperatures evident in hydrogen combustion, as detailed in Table 2, can potentially elevate NOx emissions and lead to higher levels of water vapor in the exhaust relative to carbon-containing fuels. This presents a challenge in meeting emissions standards and could contribute to heightened contrail formation [68].

Table 2. Hydrogen and ammonia flame properties [61]

Fuel	H_2	NH_3
Maximum laminar flame speed (cm/s)	291	7
Adiabatic flame temperature (K)	2400	2075
Flammability range	0.1-7.1	0.6-1.4
Critical temperature (K) and pressure (MPa)	33 and 13	405 and 11.3
Triple point temperature (K) and pressure (MPa)	14 and 0.07	195 and 0.006

In summary, while e-H_2 offers numerous attractive features as a zero-carbon aviation fuel, it is accompanied by distinct handling and safety challenges. Innovative solutions are required to address various emission concerns associated with its use [69]. However, e-H_2 can be employed to synthesize another molecule with simpler handling requirements, eliminating the necessity for cryogenic liquefaction or high-pressure storage. In this context, ammonia arises as an excellent H_2 carrier, capable of being catalytically broken down to release H2 gas before combustion. This approach offers potential pathways to minimize overall emissions. [70]. Ammonia (NH_3) exhibits a liquid state over a considerably wider temperature range than hydrogen and enjoys the advantages of a well-established supply chain. When utilized as a hydrogen carrier, ammonia showcases superior endothermic fuel properties relative to kerosene. Maintaining its liquid state at 240 K under ambient pressure, ammonia absorbs energy during decomposition and avoids coke production. However, direct combustion of ammonia reduces the fuel's thermal sink capacity compared to a cracking technique [71].

In addition to the comprehensive assessment of e-H_2 and its potential as a zero-carbon aviation fuel, it is essential to consider the broader implications and ongoing research in the field of alternative aviation fuels. One crucial aspect to address is the scalability and infrastructure development necessary to support widespread adoption. While e-H_2 holds promise, its successful integration into commercial aviation operations hinges on overcoming logistical challenges, such as refueling infrastructure and supply chain management.

Furthermore, exploring synergies with existing technologies and alternative fuel sources could yield innovative solutions to the challenges associated with hydrogen-based propulsion systems. For instance, hybrid propulsion systems combining e-H_2 with other renewable energy sources, such as solar or wind power, could enhance efficiency and reduce overall emissions.

Moreover, the discussion could delve into the importance of regulatory frameworks and industry collaboration in driving forward the adoption of sustainable aviation fuels. Governments, airlines, and industry stakeholders must work together to establish clear standards, incentives, and investment mechanisms to facilitate the transition to zero-emission aviation.

Lastly, it is crucial to highlight ongoing research efforts aimed at addressing the environmental and safety concerns associated with alternative fuels. Whether through advancements in combustion technologies, emissions reduction strategies, or novel fuel synthesis methods, continuous innovation will be essential in realizing the vision of sustainable aviation.

By expanding the discussion to encompass these broader considerations, the result and discussion section can provide a more comprehensive overview of the current landscape and future prospects for zero-carbon.

CONCLUSIONS

As the aviation industry strives to mitigate its environmental impact and work towards achieving net-zero emissions, exploring alternative fuel options becomes imperative. The urgency of addressing climate change has propelled the industry to look beyond conventional fuels, recognizing that the path to sustainability is not a singular one but involves a diverse portfolio of energy solutions. While current technical and technological limitations may hinder immediate implementation, it is crucial to recognize the significance of these alternatives in shaping the future of aviation sustainability. Each alternative fuel, from biofuels to hydrogen-based solutions, presents a unique opportunity to significantly reduce emissions, paving the way for a greener aviation sector.

The environmental benefits of SAFs are underscored by their ability to decrease lifecycle emissions considerably. For instance, SAFs derived from processes such as Fischer-Tropsch synthesis have shown potential reductions of up to 68% in CO_2 emissions. These advantages make SAFs an essential component of aviation's strategy to reduce its carbon footprint, particularly as regulatory pressures increase and the demand for sustainable practices intensifies.

Regarding scalability, SAF production must overcome feedstock limitations and supply chain complexities. Diverse feedstock options present varied environmental and economic trade-offs, with some sources raising concerns related to food security and land use. Therefore, establishing a sustainable and reliable feedstock supply chain is crucial to scaling SAF production without compromising other environmental or social factors. The economic potential of SAFs not only in direct employment within the production and distribution sectors but also in the broader economic growth stimulated by a sustainable aviation industry. With strategic planning, SAF production could become a catalyst for local economic development, particularly in rural areas where biomass feedstocks are abundant.

However, the transition to sustainable aviation is not without its challenges. While e-H_2 (electrolytic hydrogen) presents compelling advantages in energy density and performance metrics, challenges such as storage complexities, emission concerns, and infrastructure requirements remain significant hurdles to widespread adoption. The ongoing research and development efforts aimed at addressing these challenges highlight the industry's dedication to innovation and sustainability. In particular, the development of advanced storage solutions, such as cryogenic tanks for hydrogen, and the establishment of robust supply chains for green hydrogen are critical components of this transition. Collaborative initiatives between governments, airlines, and industry stakeholders are essential in overcoming logistical barriers and establishing regulatory frameworks conducive to the transition to sustainable aviation fuels.

Furthermore, the synergistic integration of e-H_2 with complementary technologies and alternative fuel sources offers promising avenues for enhancing efficiency and reducing emissions. Hybrid propulsion systems, which combine the strengths of both conventional and alternative fuels, and novel synthesis methods for SAFs represent innovative approaches to maximizing the potential of e-H_2 while minimizing environmental impact. These technologies not only enhance the operational efficiency of aircraft but also provide a more flexible and scalable solution to the industry's sustainability challenges.

As the aviation sector strives to achieve net-zero emissions by the 2050s, continued investment in research, infrastructure, and regulatory support will be critical. This includes the development of policies that incentivize the adoption of SAFs, establishing carbon markets that accurately reflect the environmental cost of emissions, and creating international standards that ensure the safety and reliability of new fuel technologies. By embracing a holistic approach that addresses technical, economic, and environmental considerations, the industry can pave the way for a greener, more sustainable future of air travel.

While challenges remain, the prospects for zero-carbon aviation fuels are promising, and concerted efforts across the aviation ecosystem will be instrumental in realizing this vision. Through perseverance, collaboration, and innovation, the aviation industry can lead the transition to a more sustainable and resilient future. This journey toward sustainability benefits the environment and secures the long-term viability of the aviation industry in a world increasingly prioritizing ecological responsibility. By adopting SAFs and investing in ongoing innovation, the aviation sector can position itself as a leader in sustainability, reducing its carbon footprint while supporting broader economic and environmental objectives. This journey toward a sustainable aviation industry not only addresses immediate environmental concerns but also ensures a resilient, sustainable future for air travel in an increasingly eco-conscious world. As the sector navigates the complex landscape of energy transition, the collective actions taken today will determine the trajectory of air travel for decades to come, ensuring that the skies remain a symbol of progress and a gateway to a cleaner, brighter future.

NOMENCLATURE

CO_2 : carbon dioxide
H_2 : hydrogen
LNG : liquefied natural gas
NOX : nitrogen oxides
NH_3 : ammonia
RTK : revenue tonne kilometre
SAF : sustainable aviation fuel
SOFC : solid oxide fuel cell

DATA AVAILABILITY STATEMENT

No data was used for the research described in the article.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

1. B. Graver, D. Rutherford, and S. Zheng, "CO2 Emissions from Commercial Aviation: 2013, 2018, and 1029," International Council on Clean Transportation, Oct. 2020. [Online]. Available: https://theicct.org/publication/co2-emissions-from-commercial-aviation-2013-2018-and-2019/
2. A. R. Goetz, "Air passenger transportation and growth in the US urban system, 1950–1987,"

Growth and Change, vol. 23, no. 2, pp. 217–238, 1992, doi:10.1111/j.1468-2257.1992.tb00580.x.
3. IEA, "Energy intensity of commercial passenger aviation in the Net Zero Scenario, 2000-2030." [Online]. Available: https://www.iea.org/data-and-statistics/charts/energy-intensity-of-commercial-passenger-aviation-in-the-net-zero-scenario-2000-2030
4. ICAO Environment, "Environmental Protection." [Online]. Available: https://www.icao.int/environmental-protection/Pages/default.aspx
5. ATAG, "Waypoint 2050," Sep. 2021. Accessed: Feb. 14, 2024. [Online]. Available: https://aviationbenefits.org/environmental-efficiency/climate-action/waypoint-2050/
6. EA, "World Energy Outlook 2012 – Analysis," IEA. Accessed: Feb. 12, 2024. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2012
7. N. Yilmaz and A. Atmanli, "Sustainable alternative fuels in aviation," Energy, vol. 140, pp. 1378–1386, 2017, doi:10.1016/j.energy.2017.07.077.
8. World Energy Council, "World Energy Scenarios | 2019: Exploring Innovation Pathways to 2040," Sep. 2019. Accessed: Feb. 13, 2024. [Online]. Available: https://www.worldenergy.org/publications/entry/world-energy-scenarios-2019-exploring-innovation-pathways-to-2040
9. M. A. Hasan, A. A. Mamun, S. M. Rahman, K. Malik, M. I. U. Al Amran, A. N. Khondaker, O. Reshi, S. P. Tiwari, and F. S. Alismail, "Climate Change Mitigation Pathways for the Aviation Sector," Sustainability, vol. 13, no. 7, p. 3656, 2021, doi:10.3390/su13073656.
10. D. L. Daggett, R. C. Hendricks, R. Walther, and E. Corporan, "Alternate Fuels for Use in Commercial Aircraft," E-16044-1, Apr. 2008. Accessed: Feb. 17, 2024. [Online]. Available: https://ntrs.nasa.gov/citations/20080018472
11. R. W. Jenkins, M. Munro, S. Nash, and C. J. Chuck, "Potential renewable oxygenated biofuels for the aviation and road transport sectors," Fuel, vol. 103, pp. 593–599, 2013, doi:10.1016/j.fuel.2012.08.019.
12. IEA, "Share of oil final consumption by sector, 2019," IEA, Paris. [Online]. Available: https://www.iea.org/data-and-statistics/charts/share-of-oil-final-consumption-by-sector-2019
13. P. Su-Ungkavatin, L. Tiruta-Barna, and L. Hamelin, "Biofuels, electrofuels, electric or hydrogen?: A review of current and emerging sustainable aviation systems," Progress in Energy and Combustion Science, vol. 96, p. 101073, 2023, doi:10.1016/j.pecs.2023.101073.
14. J. Bosch, S. De Jong, R. Hoefnagels, and R. Slade, "Aviation biofuels: strategically important, technically achievable, tough to deliver," Imperial College London, 2017.
15. C. J. Chuck, Ed., 'Chapter 1 - The Prospects for Biofuels in Aviation', in Biofuels for Aviation, Academic Press, 2016. doi: 10.1016/B978-0-12-804568-8.00016-0.
16. C. J. Chuck, Ed., 'Chapter 2 - Feedstocks for Aviation Biofuels', in Biofuels for Aviation, Academic Press, 2016. doi: 10.1016/B978-0-12-804568-8.00016-0.
17. J. Li, R. Zhao, Y. Xu, X. Wu, S. R. Bean, and D. Wang, "Fuel ethanol production from starchy grain and other crops: An overview on feedstocks, affecting factors, and technical advances," Renewable Energy, vol. 188, pp. 223–239, 2022.
18. T. Solakivi, A. Paimander, and L. Ojala, "Cost competitiveness of alternative maritime fuels in the new regulatory framework," Transportation Research Part D: Transport and Environment, vol. 113, p. 103500, 2022, doi:10.1016/j.trd.2022.103500.
19. ICAO, 'ICAO global framework for aviation alternative fuels', 2022.
20. European Comission, 'Proposal for a regulation of the European Parliament and of the Council on ensuring a level playing field for sustainable air transport', 2021.
21. ATAG, 'Commitment to fly net zero', 2021.
22. V. Balan, "Current challenges in commercially producing biofuels from lignocellulosic biomass," International Scholarly Research Notices, vol. 2014, p. 463074, 2014.
23. S. H. Gheewala, B. Damen, and X. Shi, "Biofuels: economic, environmental and social benefits and costs for developing countries in Asia," Wiley Interdisciplinary Reviews: Climate Change, vol. 4, no. 6, pp. 497–511, 2013.
24. S. Karatzos, J. McMillan, and J. N. Saddler, "The potential and challenges of drop-in biofuels," Report for IEA Bioenergy Task 39, 2014. [Online]. Available: https://task39.sites.olt.ubc.ca/files/2014/01/Task-39-Drop-in-Biofuels-Report-FINAL-2-Oct-2014-ecopy.pdf
25. K. M. Holmgren, T. S. Berntsson, E. Andersson, and T. Rydberg, "Comparison of integration options for gasification-based biofuel production systems–Economic and greenhouse gas emission implications," Energy, vol. 111, pp. 272–294, 2016, doi:10.1016/j.energy.2016.05.059.
26. [26] H. R. Guimaraes, J. M. Bressanin, I. L. Motta, M. F. Chagas, B. C. Klein, A. Bonomi, and M. D. B. Watanabe, "Bottlenecks and potentials for the gasification of lignocellulosic biomasses and Fischer-Tropsch synthesis: A case study on the production of advanced liquid biofuels in Brazil," Energy Conversion and Management, vol. 245, p. 114629, 2021.
27. A. Arias, C. E. Nika, V. Vasilaki, G. Feijoo, M. T. Moreira, and E. Katsou, "Assessing the future prospects of emerging technologies for shipping and aviation biofuels: A critical review," Renewable and Sustainable Energy Reviews, vol. 197, p. 114427, 2024.
28. A. Nilsson, K. Shabestary, M. Brandão, and E. P. Hudson, "Environmental impacts and limitations of

third-generation biobutanol: Life cycle assessment of n-butanol produced by genetically engineered cyanobacteria," Journal of Industrial Ecology, vol. 24, no. 1, pp. 205–216, 2020.
29. C. Van Der Giesen, S. Cucurachi, J. Guinée, G. J. Kramer, and A. Tukker, "A critical view on the current application of LCA for new technologies and recommendations for improved practice," Journal of Cleaner Production, vol. 259, p. 120904, 2020.
30. E. Sevigné-Itoiz, O. Mwabonje, C. Panoutsou, and J. Woods, "Life cycle assessment (LCA): informing the development of a sustainable circular bioeconomy?," Philosophical Transactions of the Royal Society A, vol. 379, no. 2206, p. 20200352, 2021.
31. C. Panoutsou, S. Germer, P. Karka, S. Papadokostantakis, Y. Kroyan, M. Wojcieszyk, and I. Landalv, "Advanced biofuels to decarbonise European transport by 2030: Markets, challenges, and policies that impact their successful market uptake," Energy Strategy Reviews, vol. 34, p. 100633, 2021.
32. A. Dufey, Biofuels production, trade and sustainable development: emerging issues, IIED, 2006.
33. I. Ridjan, B. V. Mathiesen, and D. Connolly, "Terminology used for renewable liquid and gaseous fuels based on the conversion of electricity: a review," Journal of Cleaner Production, vol. 112, pp. 3709–3720, 2016.
34. A. Goldmann, W. Sauter, M. Oettinger, T. Kluge, U. Schröder, J. Seume, J. R. Friedrichs, and F. Dinkelacker, "A study on electrofuels in aviation," Energies, vol. 11, no. 2, p. 392, 2018.
35. M. Lehtveer, S. Brynolf, and M. Grahn, "What future for electrofuels in transport? Analysis of cost competitiveness in global climate mitigation," Environmental Science & Technology, vol. 53, no. 3, pp. 1690–1699, 2019, doi:10.1021/acs.est.8b05243.
36. R. Raman, S. Gunasekar, L. D. Dávid, A. F. Rahmat, and P. Nedungadi, "Aligning sustainable aviation fuel research with sustainable development goals: Trends and thematic analysis," Energy Reports, vol. 12, pp. 2642–2652, 2024, doi:10.1016/j.egyr.2024.08.076.
37. S. Ahmad, J. Ouenniche, B. W. Kolosz, P. Greening, J. M. Andresen, M. M. Maroto-Valer, and B. Xu, "A stakeholders' participatory approach to multi-criteria assessment of sustainable aviation fuels production pathways," International Journal of Production Economics, vol. 238, p. 108156, 2021, doi:10.1016/j.ijpe.2021.108156.
38. J. Ahlström, Y. Jafri, E. Wetterlund, and E. Furusjö, "Sustainable aviation fuels–Options for negative emissions and high carbon efficiency," International Journal of Greenhouse Gas Control, vol. 125, p. 103886, 2023, doi:10.1016/j.ijggc.2023.103886.
39. The Faraday Institute, "Faraday Report: High-Energy Battery Technologies," The Faraday Institute, 2020. [Online]. Available: https://www.faraday.ac.uk/wp-content/uploads/2020/01/High-Energy-battery-technologies-FINAL.pdf
40. N. Yilmaz and A. Atmanli, "Sustainable alternative fuels in aviation," Energy, vol. 140, pp. 1378–1386, 2017, doi:10.1016/j.energy.2017.07.077.
41. Roland Berger, 'Hydrogen: A future fuel for aviation?', Roland Berger. Accessed: Mar. 13, 2024. [Online]. Available: https://www.rolandberger.com/en/Insights/Publications/Hydrogen-A-future-fuel-for-aviation.html
42. E. J. Adler and J. R. Martins, "Hydrogen-powered aircraft: Fundamental concepts, key technologies, and environmental impacts," Progress in Aerospace Sciences, vol. 141, p. 100922, 2023, doi:10.1016/j.paerosci.2023.100922.
43. C. Marek, T. Smith, and K. Kundu, "Low emission hydrogen combustors for gas turbines using lean direct injection," in 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Jul. 2005, p. 3776. Accessed: Mar. 13, 2024. [Online]. Available: https://ntrs.nasa.gov/citations/20080002274
44. G. Dahl and F. Suttrop, "Engine control and low-NOx combustion for hydrogen fuelled aircraft gas turbines," International Journal of Hydrogen Energy, vol. 23, no. 8, pp. 695–704, 1998, doi:10.1016/S0360-3199(97)00115-8.
45. B. Khandelwal, A. Karakurt, P. R. Sekaran, V. Sethi, and R. Singh, "Hydrogen powered aircraft: The future of air transport," Progress in Aerospace Sciences, vol. 60, pp. 45–59, 2013, doi:10.1016/j.paerosci.2012.12.002.
46. F. Liu, M. Shafique, and X. Luo, "Literature review on life cycle assessment of transportation alternative fuels," Environmental Technology & Innovation, vol. 32, p. 103343, 2023, doi:10.1016/j.eti.2023.103343.
47. A. Baroutaji, T. Wilberforce, M. Ramadan, and A. G. Olabi, "Comprehensive investigation on hydrogen and fuel cell technology in the aviation and aerospace sectors," Renewable and Sustainable Energy Reviews, vol. 106, pp. 31–40, 2019, doi:10.1016/j.rser.2019.02.022.
48. M. McManus, Net Zero Aviation Fuels: resource requirements and environmental impacts policy briefing. The Royal Society, 2023. [Online]. Available: https://royalsociety.org/news/2023/02/net-zero-aviation-fuels-report/
49. T. Yusaf, A. S. F. Mahamude, K. Kadirgama, D. Ramasamy, K. Farhana, H. A. Dhahad, and A. R. A. Talib, "Sustainable hydrogen energy in aviation–A narrative review," International Journal of Hydrogen Energy, vol. 52, pp. 1026–1045, 2024, doi:10.1016/j.ijhydene.2023.02.086.
50. A. Contreras, S. Yiğit, K. Özay, and T. N. Veziroğlu, "Hydrogen as aviation fuel: a comparison with hydrocarbon fuels," International Journal of Hydrogen Energy, vol. 22, no. 10–11, pp. 1053–1060, 1997, doi:10.1016/S0360-3199(97)00008-6.
51. J. Winnefeld, T. Kadyk, B. Bensmann, U. Krewer, and R. Hanke-Rauschenbach, "Modelling and designing cryogenic hydrogen tanks for future aircraft

applications," Energies, vol. 11, no. 1, p. 105, 2018, doi:10.3390/en11010105.
52. J. Hoelzen, D. Silberhorn, T. Zill, B. Bensmann, and R. Hanke-Rauschenbach, "Hydrogen-powered aviation and its reliance on green hydrogen infrastructure–Review and research gaps," International Journal of Hydrogen Energy, vol. 47, no. 5, pp. 3108–3130, 2022, doi:10.1016/j.ijhydene.2021.10.239.
53. D. Cecere, E. Giacomazzi, and A. Ingenito, "A review on hydrogen industrial aerospace applications," International Journal of Hydrogen Energy, vol. 39, no. 20, pp. 10731–10747, 2014, doi:10.1016/j.ijhydene.2014.04.126.
54. D. Verstraete, "On the energy efficiency of hydrogen-fuelled transport aircraft," International Journal of Hydrogen Energy, vol. 40, no. 23, pp. 7388–7394, 2015,
55. M. Raab and R. U. Dietrich, "Techno-economic assessment of different aviation fuel supply pathways including LH2 and LCH4 and the influence of the carbon source," Energy Conversion and Management, vol. 293, p. 117483, 2023, doi:10.1016/j.enconman.2023.117483.
56. [56] P. Rompokos, S. Kissoon, I. Roumeliotis, D. Nalianda, T. Nikolaidis, and A. Rolt, "Liquefied natural gas for civil aviation," Energies, vol. 13, no. 22, p. 5925, 2020, doi:10.3390/en13225925.
57. A. Gangoli Rao, F. Yin, and J. P. van Buijtenen, "A hybrid engine concept for multi-fuel blended wing body," Aircraft Engineering and Aerospace Technology, vol. 86, no. 6, pp. 483–493, 2014, doi:10.1108/AEAT-04-2014-0054.
58. M. Fasihi, R. Weiss, J. Savolainen, and C. Breyer, "Global potential of green ammonia based on hybrid PV-wind power plants," Applied Energy, vol. 294, p. 116170, 2021, doi:10.1016/j.apenergy.2020.116170.
59. F. Abbasov, T. Earl, C. C. Ambel, B. Hemmings, and L. Gilliam, "Roadmap to decarbonising European shipping," Transport & Environment, 2018. [Online]. Available: https://www.transportenvironment.org/wp-content/uploads/2021/07/2018_11_Roadmap_decarbonising_European_shipping.pdf
60. G. Jeerh, M. Zhang, and S. Tao, "Recent progress in ammonia fuel cells and their potential applications," Journal of Materials Chemistry A, vol. 9, no. 2, pp. 727–752, 2021, doi:10.1039/D0TA08810B.
61. M. Otto, L. Vesely, J. Kapat, M. Stoia, N. D. Applegate, and G. Natsui, "Ammonia as an aircraft fuel: A critical assessment from airport to wake," ASME Open Journal of Engineering, vol. 2, 2023, doi:10.1115/1.4062626.
62. NREL, 'Best Research-Cell Efficiency Chart'. Accessed: Mar. 14, 2024. [Online]. Available: https://www.nrel.gov/pv/cell-efficiency.html
63.] F. Salazar, M. S. Martinez-Garcia, A. de Castro, N. Logroño, M. F. Cazorla-Logroño, J. Guamán-Molina, and C. Gómez, "Optimization of the solar energy storage capacity for a monitoring UAV," Sustainable Futures, vol. 7, p. 100146, 2024, doi:10.1016/j.sftr.2023.100146.
64. A. Machín and F. Márquez, "Advancements in photovoltaic cell materials: silicon, organic, and perovskite solar cells," Materials, vol. 17, no. 5, p. 1165, 2024, doi:10.3390/ma17051165.
65. McKinsey, 'Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation', World Economic Forum, Nov. 2020. [Online]. Available: https://www3.weforum.org/docs/WEF_Clean_Skies_Tomorrow_SAF_Analytics_2020.pdf
66. Boeing, 'Commercial Market Outlook 2021-2040', Boeing, 2021. [Online]. Available: https://www.boeing.com/content/dam/boeing/boeingdotcom/market/assets/downloads/CMO%202021%20Report_13Sept21.pdf
67. M. Otto, M. P. Sargunaraj, A. Riahi, and J. Kapat, "A novel long-duration hydrogen storage concept without liquefaction and high pressure suitable for onsite blending," in Turbo Expo: Power for Land, Sea, and Air, Jun. 2021, vol. 84997, p. V006T03A007, doi:10.1115/GT2021-59393.
68. L. Bock and U. Burkhardt, "Contrail cirrus radiative forcing for future air traffic," Atmospheric Chemistry and Physics, vol. 19, no. 12, pp. 8163–8174, 2019, doi:10.5194/acp-19-8163-2019.
69. C. Chu, K. Wu, B. Luo, Q. Cao, and H. Zhang, "Hydrogen storage by liquid organic hydrogen carriers: catalyst, renewable carrier, and technology–a review," Carbon Resources Conversion, vol. 6, no. 4, pp. 334–351, 2023, doi:10.1016/j.crcon.2023.03.007.
70. M. Aziz, A. T. Wijayanta, and A. B. D. Nandiyanto, "Ammonia as effective hydrogen storage: A review on production, storage and utilization," Energies, vol. 13, no. 12, p. 3062, 2020, doi:10.3390/en13123062.
71. W. Raróg-Pilecka, D. Szmigiel, A. Komornicki, J. Zieliński, and Z. Kowalczyk, "Catalytic properties of small ruthenium particles deposited on carbon. Ammonia decomposition studies," Carbon, vol. 41, no. 3, pp. 589–591, 2003, doi:10.1016/S0008-6223(02)00393-7.