AVIATION AND SECURITY ISSUES NO. 4(2/2023)
ISSN 2720-197X / eISSN 2956-3380

Paweł GOŁDA
Polish Air Force University
e-mail: p.golda@law.mil.pl; ORCID: 0000-0003-4066-7814

Krzysztof CUR
Polish Air Force University
e-mail: k.cur@law.mil.pl; ORCID: 0000-0003-4552-445X

Tadeusz ZAWORSKI
Air Force Institute of Technology
e-mail: tadeusz.zaworski@itwl.pl; ORCID: 0000-0002-3875-2027

Adam RURAK
Polish Air Force University
e-mail: a.rurak@law.mil.pl; ORCID: 0000-0002-5842-8048

DOI: 10.55676/asi.v4i2.86

INNOVATIVE DIRECTIONS IN AIR TRANSPORT: ANALYSIS OF NEW ENERGY SOURCES

INNOWACYJNE KIERUNKI W TRANSPORCIE LOTNICZYM: ANALIZA NOWYCH ŹRÓDEŁ ENERGII

Abstract

This article provides a comprehensive analysis of the potential for the application of alternative energy storage sources, such as batteries, hydrogen, and biofuels, in air transport. In the context of growing concern for environmental aspects and the need to reduce greenhouse gas emissions, the focus is on identifying the benefits and limitations of these technologies as alternatives to traditional aviation fuels. The article discusses in detail various aspects related to the use of batteries, analyzing their potential in the context of aircraft. Furthermore, the prospects associated with the use of hydrogen as an energy carrier are assessed, considering technical, economic and safety aspects. In addition, an analysis of the potential of biofuels as an alternative is presented, taking into account issues of sustainable access to raw materials. The analysis also covers economic and technical aspects, considering efficiency, safety, and impact on aircraft weight. The article highlights the key role of the search for new sustainable energy sources in air transport and presents the prospects and challenges for the introduction of batteries, hydrogen and biofuels in this sector. The analyses presented in the article are an important contribution to the discussion on the green development of air transport.

Keywords: batteries, biofuels, aviation, new sources of energy, hydrogen

Streszczenie

W ramach niniejszego artykułu przeprowadzono wszechstronną analizę potencjału zastosowania alternatywnych źródeł magazynowania energii, takich jak baterie, wodór i biopaliwa, w transporcie lotniczym. W kontekście narastającej troski o aspekty środowiskowe oraz konieczności ograniczenia emisji gazów cieplarnianych, skoncentrowano się na identyfikacji korzyści i ograniczeń tych technologii jako alternatywy dla tradycyjnych paliw lotniczych. Artykuł szczegółowo omawia różne aspekty związane z zastosowaniem baterii, analizując ich potencjał w kontekście samolotów. Ponadto, dokonano oceny perspektyw związanych z zastosowaniem wodoru jako nośnika energii, uwzględniając aspekty techniczne, ekonomiczne i bezpieczeństwa. Dodatkowo, przedstawiono analizę potencjału biopaliw jako alternatywy, uwzględniając kwestie zrównoważonego dostępu do surowców. Przeprowadzona analiza obejmuje również aspekty ekonomiczne i techniczne, uwzględniając wydajność, bezpieczeństwo i wpływ na masę samolotu. Artykuł zaznacza kluczową rolę poszukiwań nowych, zrównoważonych źródeł energii w transporcie lotniczym oraz przedstawia perspektywy i wyzwania związane z wprowadzeniem baterii, wodoru i biopaliw w tym sektorze. Analizy prezentowane w artykule stanowią istotny wkład w dyskusję nad ekologicznym rozwojem transportu lotniczego.

Słowa kluczowe: baterie, biopaliwa, lotnictwo, nowe źródła energii, wodór

Artykuł wpłynął do redakcji: 11.10.2023 / Zatwierdzono do publikacji: 30.12.2023

1. INTRODUCTION

1.1. OVERVIEW OF CURRENT AIR TRANSPORT ENERGY SOURCES

The historical context and evolution of energy sources in air transport have indeed shifted towards more sustainable and environmentally friendly options. Traditional jet fuels, derived from crude oil, have historically dominated the aviation sector[1]. However, the continued reliance on hydrocarbon jet fuel does pose a threat to global CO_2 emissions, with projections suggesting a potential increase in aviation's contribution to emissions by 2050[2].

To tackle this challenge, there has been a notable rise in interest in alternative energy sources for air transport. One promising avenue is the development of sustainable aviation fuels, which are crucial for achieving carbon-neutral growth in aviation[3]. These alternative drop-in fuels, incorporating biobased components, provide a pathway to reduce the environmental impact of air travel. Biojet fuels, derived from biomass feedstock, have demonstrated potential in decarbonizing air transport, particularly when combined with carbon capture and storage technologies[4].

In addition to sustainable aviation fuels, advancements in battery technology have also attracted attention as potential energy sources for air transport. Metal-air batteries, such as zinc-air batteries, are under exploration for their high theoretical energy output and potential applications in electrified transportation[5]. Rechargeable zinc-air batteries are particularly promising due to their high energy density, safety, and environmental friendliness, positioning them as a viable technology for renewable energy devices[6].

Furthermore, the power-to-liquid pathway has emerged as a renewable fuel option for aviation, utilizing renewable electricity, CO_2, and water to synthesize sustainable alternative fuels that closely resemble conventional jet fuel[7]. This approach offers a means to produce aviation fuels with reduced environmental impact, contributing to the overall sustainability of air transport.

Summarizing, the overview of current air transport energy sources underscores a transition towards more sustainable options, including sustainable aviation fuels, advanced battery technologies like zinc-air batteries, and innovative pathways such

1 Yakovlieva et al., 'Experimental Study of Physical-Chemical Properties of Advanced Alcohol-to-Jet Fuels.'
2 Seiple, 'Cost-Effective Opportunities to Produce Sustainable Aviation Fuel From Low-Cost Wastes in the U.S.'
3 Trinh et al., 'What Are the Policy Impacts on Renewable Jet Fuel in Sweden?'
4 Wise, Muratori, and Kyle, 'Biojet Fuels and Emissions Mitigation in Aviation: An Integrated Assessment Modeling Analysis.'
5 Cheng and Chen, 'Metal–Air Batteries: From Oxygen Reduction Electrochemistry to Cathode Catalysts.'
6 Zhang et al., 'An Ultrastable Rechargeable Zinc–Air Battery Using a Janus Superwetting Air Electrode.'
7 Schmidt et al., 'Power-to-Liquids as Renewable Fuel Option for Aviation: A Review.'

 DOI: 10.55676/asi.v4i2.86

as power-to-liquid fuels. These developments signify a concerted effort within the aviation industry to mitigate carbon emissions and enhance the environmental sustainability of air travel.

1.2. NEED FOR INNOVATION

The necessity for innovation in the air transport sector is driven by a variety of factors, including environmental impact, regulatory pressures, economic considerations, and technological advancements. Environmental concerns, particularly regarding carbon emissions and climate change, have resulted in increased regulatory pressures on the aviation industry to decrease its carbon footprint[8]. Technologies such as carbon capture and sequestration (CCS) are being explored to mitigate CO_2 emissions from aviation activities[9]. Additionally, the development of sustainable aviation fuels and advancements in battery technology, such as zinc-air batteries, offer promising solutions to address the environmental impact of air transport.

Economic factors also significantly influence innovation in the air transport sector. The shift to more sustainable energy sources is not only motivated by environmental concerns but also by the economic benefits associated with cost efficiency and long-term sustainability[10]. Research indicates that investing in renewable energy sources and energy-efficient technologies can lead to economic savings and contribute to the overall sustainability of the transportation sector[11].

Furthermore, technological advancements are essential for the feasibility and implementation of innovative solutions in air transport. Advanced electrocatalysis and materials science play a crucial role in enhancing energy conversion efficiency and durability of energy technologies, thereby facilitating the adoption of sustainable energy sources in aviation[12]. Additionally, the integration of renewable energy systems, such as solar energy, offers feasible alternatives for reducing carbon emissions and enhancing energy efficiency in air transport[13].

To sum up, the imperative for innovation in the air transport sector is steered by a combination of environmental, economic, and technological factors. By leveraging advancements in sustainable aviation fuels, battery technologies, carbon capture, and renewable energy sources, the aviation industry can progress towards reducing its environmental impact, improving cost efficiency, and embracing more sustainable practices.

8 Jones, ‘CO_2 Capture From Dilute Gases as a Component of Modern Global Carbon Management.’
9 Lackner et al., ‘The Urgency of the Development of CO ₂ Capture From Ambient Air.’
10 Zhao et al., ‘Carbon Emissions Peak in the Road and Marine Transportation Sectors in View of Cost-Benefit Analysis: A Case of Guangdong Province in China.’
11 Corlu et al., ‘Optimizing Energy Consumption in Transportation: Literature Review, Insights, and Research Opportunities.’
12 Barkakaty et al., ‘Emerging Materials for Lowering Atmospheric Carbon.’
13 Choi and Kim, ‘Analysis of Solar Energy Utilization Effect of Air-Based Photovoltaic/Thermal System.’

2. ENVIRONMENTAL AND ECONOMIC IMPERATIVES

2.1. ENVIRONMENTAL CHALLENGES

Climate change and greenhouse gas emissions present significant environmental challenges for the aviation industry. Aviation contributes to global greenhouse gas emissions, with the sector responsible for approximately 2% of total global emissions, a figure that is projected to rise to 3% by 2050[14].

The International Civil Aviation Organization (ICAO) and the Paris Agreement have set targets to limit the increase in global average temperature, necessitating substantial reductions in greenhouse gas emissions across all sectors, including aviation[15]. The aviation industry faces the imperative to align with international regulations and targets to mitigate its environmental impact and contribute to global efforts to combat climate change.

2.2. INTERNATIONAL REGULATIONS AND TARGETS

The aviation sector operates within a framework of international regulations and targets established by organizations like the ICAO and agreements such as the Paris Agreement. The ICAO, in response to the Paris Agreement and the UN Sustainable Development Goals, has recognized the need for more ambitious goals to achieve sustainable aviation and has been exploring long-term global aspirational goals aligned with the temperature goals of the Paris Agreement[16]. The Paris Agreement, which aims to limit global warming to well below 2°C, requires significant reductions in greenhouse gas emissions from all sectors, including aviation[17]. These international regulations and targets underscore the urgency for the aviation industry to adopt sustainable practices and reduce its environmental footprint to contribute to global climate mitigation efforts.

In conclusion, the environmental challenges faced by the aviation industry, including climate change and greenhouse gas emissions, necessitate adherence to international regulations and targets set by organizations like the ICAO and agreements such as the Paris Agreement. By aligning with these frameworks, the aviation sector can work towards reducing its environmental impact and contributing to global efforts to address climate change.

2.3. ECONOMIC PRESSURES

Fuel costs and market volatility are critical economic pressures that significantly impact the aviation industry. Among various fuel commodities, kerosene stands out as

14 Yin, 'A Study of Carbon Dioxide Emissions Reduction Opportunities for Airlines on Australian International Routes.'
15 Schmidt et al., 'Power-to-Liquids as Renewable Fuel Option for Aviation: A Review.'
16 Fuglestvedt et al., 'A 'Greenhouse Gas Balance' for Aviation in Line With the Paris Agreement.'
17 Schmidt et al., 'Power-to-Liquids as Renewable Fuel Option for Aviation: A Review.'

 DOI: 10.55676/asi.v4i2.86

the most widely used and cost-effective fuel in aviation[18]. Fluctuations in fuel prices can have a substantial effect on airlines' operational costs and profitability, necessitating strategies to manage fuel expenses effectively. Economic incentives for adopting new energy sources, such as sustainable aviation fuels, are increasingly attractive due to the potential cost savings and long-term benefits associated with reducing reliance on traditional jet fuels[19]. Operational and financial hedging strategies play a crucial role in mitigating airline exposure to jet fuel price risk and market uncertainties, highlighting the importance of proactive risk management in the face of economic fluctuations[20]. The impact of fuel prices on airlines' capacity choices and operational performance underscores the need for strategic fuel efficiency measures to enhance economic sustainability within the aviation sector[21].

Case studies of airlines and economies impacted by fuel prices provide valuable insights into the real-world implications of fuel cost fluctuations. Studies examining the effects of fuel price volatility on airlines' performance and profitability shed light on the challenges faced by the industry in managing operational costs and maintaining competitiveness[22]. The economic significance of fuel prices is further underscored by research highlighting the correlation between fuel price fluctuations, macroeconomic variables, and airlines' financial performance, emphasizing the need for comprehensive cost-control measures and risk mitigation strategies[23]. As the aviation industry navigates economic uncertainties, the adoption of sustainable fuel alternatives, such as bio-jet fuels, emerges as a promising avenue to address both economic and environmental concerns.

In summary, fuel costs, market volatility, and economic incentives for adopting new energy sources are pivotal economic factors shaping the aviation industry's operational landscape. By implementing effective fuel efficiency measures, risk management strategies, and sustainable fuel solutions, airlines can enhance their economic resilience, reduce environmental impact, and ensure long-term sustainability in a dynamic and competitive market environment.

3. HYDROGEN AS AN ALTERNATIVE FUEL

Hydrogen is rapidly emerging as a leading candidate to power the future of aviation, driven by its unique properties and potential to drastically cut greenhouse gas emissions. As the most abundant element in the universe, hydrogen's versatility and clean combustion make it an attractive alternative to traditional fossil fuels. This section delves into the potential and challenges of utilizing hydrogen in aviation,

18 Baroutaji et al., 'Comprehensive Investigation on Hydrogen and Fuel Cell Technology in the Aviation and Aerospace Sectors.'

19 Singh and Kumar Sharma, 'Evolving Base for the Fuel Consumption Optimization in Indian Air Transport: Application of Structural Equation Modeling.'

20 Treanor et al., 'Does Operational and Financial Hedging Reduce Exposure? Evidence From the U.S. Airline Industry.'

21 Turner and Lim, 'Hedging Jet Fuel Price Risk: The Case of U.S. Passenger Airlines.'

22 Nygren, Aleklett, and Höök, 'Aviation Fuel and Future Oil Production Scenarios.'

23 Piranti, 'The Impact of Fuel Price Fluctuation and Macroeconomic Variables to Airlines Performance.'

emphasizing technological advancements, infrastructural needs, and the hurdles that must be overcome for widespread adoption.

Hydrogen offers several compelling benefits as an aviation fuel. One of its most notable advantages is its abundance. Hydrogen can be produced from a variety of sources, including water through electrolysis, natural gas via steam methane reforming, and biomass. This versatility ensures a robust supply chain that can be tailored to different regions resources. The clean combustion of hydrogen is another significant advantage. When burned, hydrogen produces only water vapor, eliminating carbon dioxide and other greenhouse gas emissions associated with conventional jet fuels. This characteristic positions hydrogen as a key player in reducing aviation's carbon footprint, aligning with global efforts to combat climate change. Furthermore, hydrogen boasts a high energy density, roughly three times that of traditional jet fuel. This high specific energy makes hydrogen particularly suitable for long-haul flights and heavy-duty aviation applications, offering the potential for extended range and improved efficiency.

One of the most promising technological advancements in the aviation sector is hydrogen fuel cell technology. Fuel cells generate electricity through an electrochemical reaction between hydrogen and oxygen, producing water as the only byproduct. This process is highly efficient and generates zero emissions, making it an attractive option for powering electric propulsion systems in aircraft. The adoption of hydrogen fuel cells can also reduce noise pollution and maintenance costs due to fewer moving parts compared to conventional jet engines. For hydrogen to be viable in aviation, efficient storage and distribution systems are essential. Liquid hydrogen, with its higher energy density compared to gaseous hydrogen, is the preferred form for aviation applications. However, storing liquid hydrogen requires cryogenic temperatures around -253°C and specialized insulated tanks. Developing infrastructure for the large-scale production, storage, and distribution of liquid hydrogen is crucial. Airports need to be equipped with the necessary facilities to handle liquid hydrogen safely and efficiently, ensuring a seamless supply chain from production to aircraft refueling. The shift to hydrogen fuel necessitates significant modifications in aircraft design. Current research focuses on developing airframes, fuel tanks, and propulsion systems that can efficiently utilize hydrogen. These designs must also incorporate robust safety measures to handle hydrogen's flammability. Innovative solutions include using composite materials for lighter and more efficient tanks and redesigning propulsion systems to accommodate hydrogen fuel cells or direct combustion engines. These advancements are pivotal in making hydrogen-powered aviation a reality.

Despite its potential, hydrogen faces significant production and storage challenges. Most hydrogen today is produced from natural gas, a process that emits carbon dioxide. To fully leverage hydrogen's environmental benefits, green hydrogen production methods, such as electrolysis powered by renewable energy, must be scaled up. Additionally, storing hydrogen, particularly in liquid form, is technically challenging due to the need for cryogenic temperatures and high-pressure tanks. Advances in material science and cryogenic technology are essential to overcome these hurdles.

 DOI: 10.55676/asi.v4i2.86

Hydrogen's flammability raises safety concerns, especially in the context of aviation. Ensuring the safe handling, storage, and transportation of hydrogen requires advanced safety protocols and materials. Public perception also poses a challenge, as historical incidents like the Hindenburg disaster have left lasting negative impressions. Educating the public about modern hydrogen technologies and their stringent safety measures is vital to gaining broader acceptance. The economic viability of hydrogen as an aviation fuel hinges on reducing production and infrastructure costs. Currently, the high cost of green hydrogen production limits its competitiveness with traditional fuels. However, technological advancements and economies of scale are expected to drive down costs over time. Government policies and incentives will play a crucial role in fostering a supportive environment for hydrogen adoption in aviation, helping to bridge the gap until the technology becomes economically self-sustaining.

Summarizing, hydrogen holds immense potential as an alternative fuel for aviation, offering significant environmental benefits and high energy efficiency. However, realizing this potential requires overcoming substantial challenges in production, storage, safety, and economic viability. Collaborative efforts from industry, government, and research institutions are essential to drive innovation and investment in hydrogen technologies. With continued progress, hydrogen can pave the way for a sustainable and environmentally friendly future in air transport.

4. ELECTRIC PROPULSION SYSTEMS

The aviation industry has increasingly focused on developing technologies to reduce its environmental impact. Traditional combustion engines in aircraft contribute significantly to CO_2 emissions, noise pollution, and high operational costs. In response, fully electric and hybrid-electric aircraft are emerging as promising alternatives. These new designs aim to be zero-emission, quiet, and cost-effective, potentially replacing the heavily fossil fuel-dependent aviation industry. Electric engines, both fully electric and hybrid-electric, can be powered by lithium-ion or lithium-air batteries, achieving near-zero or significantly reduced emissions. However, the development of electric aviation faces significant challenges, including battery performance, charging technology, battery recycling, and electric propulsion technology.

One of the primary challenges in the development of electric aviation is the current performance limitations of batteries. The energy density of available battery technologies is still relatively low compared to traditional jet fuel. This limitation affects the range and payload capacity of electric aircraft, making them less competitive for long-haul flights. Additionally, battery weight is a critical factor. While lithium-ion batteries are currently the most advanced and widely used, their weight can significantly impact the aircraft overall efficiency and performance.

Charging technology also presents a significant challenge. Rapid and efficient charging solutions are necessary to minimize downtime and ensure the viability of electric aircraft for commercial use. Current charging infrastructure is inadequate, and developing a network of charging stations, especially at airports, will require substantial investment and coordination.

Battery recycling is another critical issue. As the adoption of electric aviation grows, the need for effective recycling methods will become increasingly important to manage the environmental impact of used batteries. Developing sustainable recycling processes that can handle the specific materials used in aviation-grade batteries is essential.

Electric propulsion technology is still in its infancy compared to conventional combustion engines. While significant advancements have been made, further research and development are needed to improve the efficiency, reliability, and safety of electric propulsion systems. The integration of these systems into existing aircraft designs also poses engineering challenges, requiring modifications to airframes, control systems, and maintenance procedures.

The transition to electric aviation will require comprehensive research and technological improvements to overcome these limitations. Despite these challenges, the potential benefits of electric aviation, including reduced emissions, lower noise pollution, and decreased operational costs, make it a promising area for future development.

5. USE OF BIOFUELS INSTEAD OF TRADITIONAL FUEL

Biofuels have emerged as a promising alternative in the aviation industry to reduce greenhouse gas emissions and dependency on fossil fuels. The use of aviation biofuels has shown potential in reducing emissions by 10-15%[24]. Biokerosene, a popular biofuel in aviation, offers the advantage of not requiring structural changes in aeronautical engines[25]. Stakeholders in the commercial aviation sector advocate for biofuels to lower emissions and fossil fuel dependency within existing aircraft technology and infrastructure[26]. Strategic planning for the supply chain of aviation biofuel, including the consideration of hydrogen production, is seen as a viable strategy to reduce the carbon footprint associated with the aviation sector. Studies utilizing the Aviation Integrated Model (AIM) highlight biojet fuels as crucial for potential emissions reductions in aviation[27]. The aviation industry aims to produce carbon-neutral and cost-competitive synthetic biofuels that are compatible with existing infrastructure. Research indicates that sustainable aviation fuel is successfully utilized in air transport[28]. The use of drop-in capable alternative fuels in aircraft can aid the European aviation sector in achieving sustainable development goals. Sustainable aviation fuel (SAF) is considered a potential option to reduce emissions[29]. Investigations into substituting standard jet fuel with second-generation biofuels are underway

24 Baxter, 'The Use of Aviation Biofuels as an Airport Environmental Sustainability Measure: The Case of Oslo Gardermoen Airport.'

25 Girardi et al., 'Potential of Babassu Biofuels Use as Aviation Fuel.'

26 Gegg, Budd, and Ison, 'Stakeholder Views of the Factors Affecting the Commercialization of Aviation Biofuels in Europe.'

27 Wise, Muratori, and Kyle, 'Biojet Fuels and Emissions Mitigation in Aviation: An Integrated Assessment Modeling Analysis.'

28 Izdebski, Jacyna-Gołda, and Gołda, 'Minimisation of the Probability of Serious Road Accidents in the Transport of Dangerous Goods.'

29 Ziółkowski et al., 'Method for Calculating the Required Number of Transport Vehicles Supplying Aviation Fuel to Aircraft during Combat Tasks.'

 DOI: 10.55676/asi.v4i2.86

to make aviation greener. To ensure a sustainable future, the aviation sector must reduce fossil jet fuel usage by incorporating sustainable aviation fuel. Aviation biofuels, derived from renewable feedstocks, are perceived as inherently sustainable. Demonstration flights using biofuels have been conducted globally, showcasing the feasibility of blends with regular jet fuel. The successful trials of biofuel technology in aviation aim to minimize the carbon footprint.

The utilization of biofuels in aviation presents a promising pathway towards reducing emissions and promoting sustainability in the industry. With ongoing research and advancements in biofuel technology, the aviation sector is poised to embrace biofuels as a key component in its journey towards a greener future.

6. COMPARATIVE CASE STUDY: ALTERNATIVE FUELS VS. TRADITIONAL FUEL IN PZL M-28 BRYZA AND C-130E HERCULES

In this study, we explore the feasibility of using alternative fuels: batteries, hydrogen, and biofuels in aviation, using the PZL M-28 Bryza and C-130E Hercules as case studies. These aircraft were selected due to their diverse operational profiles and the detailed data available on their performance. By analyzing these specific cases, we aim to draw broader conclusions about the potential and challenges of adopting alternative fuels in the aviation sector.

Energy Density and Range

PZL M-28 Bryza

– Batteries: Using 2000 kg of lithium-ion batteries, the Bryza achieves a range of 540 km. This is significantly less than its 1600 km range with Jet A-1 fuel.
– Hydrogen: With 3000 kg of liquid hydrogen, the range extends to 5877 km, highlighting hydrogen's high energy density.
– Biofuels: Biodiesel results in a range of 1378 km, less than Jet A-1 but still substantial.

C-130E Hercules

– Batteries: The range for the Hercules using batteries is markedly lower than with traditional fuel, underscoring current limitations in battery technology.
– Hydrogen: The hydrogen-fueled Hercules shows a dramatic range increase, similar to the Bryza.
– Biofuels: Biodiesel provides a moderate range increase compared to Jet A-1.

Aircraft	Fuel Type	Specific Energy [MJ/kg]	Fuel Weight [kg]	Range [km]
PZL M-28 Bryza	Jet A-1	43	2000	1600
PZL M-28 Bryza	Batteries	7.2	2000	540
PZL M-28 Bryza	Hydrogen	120	3000	5877
PZL M-28 Bryza	Biodiesel	37	2000	1378
C-130E Hercules	Jet A-1	43	27834	11300
C-130E Hercules	Batteries	7.2	27834	5200
C-130E Hercules	Hydrogen	120	27834	16950
C-130E Hercules	Biodiesel	37	27834	10000

Environmental Impact

PZL M-28 Bryza

- Batteries: Zero emissions during flight, but environmental impact from battery production and disposal must be considered.
- Hydrogen: Zero emissions during flight, provided hydrogen is produced using renewable energy.
- Biofuels: Reduced CO_2 emissions compared to Jet A-1, but higher than batteries and hydrogen.

C-130E Hercules

- Batteries: Similar environmental benefits and challenges as the Bryza.
- Hydrogen: Significant emission reductions, with infrastructure and production impacts.
- Biofuels: Moderate emissions reduction.

Economic Viability

PZL M-28 Bryza

- Batteries: High initial cost and infrastructure requirements.
- Hydrogen: High infrastructure and production costs, potential long-term savings.
- Biofuels: Moderate cost increase, feasible with current infrastructure.

C-130E Hercules

- Batteries: High costs, similar challenges as Bryza.
- Hydrogen: Similar economic considerations as Bryza.
- Biofuels: Feasible with moderate cost increase.

By integrating detailed case studies of the PZL M-28 Bryza and C-130E Hercules, this article provides a comprehensive analysis of the potential and challenges of using batteries, hydrogen, and biofuels in aviation. The findings highlight the trade-offs between different alternative fuels and underscore the need for continued research and innovation to achieve sustainable aviation.

7. CONCLUSIONS

The exploration of alternative energy sources in aviation, including batteries, hydrogen, and biofuels, presents both significant opportunities and challenges for the industry. The primary motivation behind these innovations is to reduce greenhouse gas emissions, lower operational costs, and decrease dependency on non-renewable fossil fuels. This study has highlighted the potential and limitations of these alternative energy sources through theoretical analysis and practical case studies.

The use of batteries, particularly lithium-ion, offers a promising pathway towards zero-emission aviation. The transition to electric aircraft could significantly reduce CO_2 emissions and noise pollution, enhancing the environmental sustainability of air travel. However, current battery technology faces significant challenges, including limited energy density, high weight, and the need for a robust recharging infrastructure. These limitations impact the range and payload capacity of electric aircraft, making

 DOI: 10.55676/asi.v4i2.86

them less viable for long-distance flights. Additionally, the high cost of batteries and the need for efficient recycling methods present further obstacles. Despite these challenges, advancements in battery technology and infrastructure development are crucial for the widespread adoption of electric aviation.

Hydrogen holds immense potential as an aviation fuel due to its high energy density and clean combustion, which produces only water vapor. This makes hydrogen a key candidate for reducing the aviation industry’s carbon footprint. The study of hydrogen application in the C-130E Hercules aircraft demonstrated that hydrogen could significantly increase flight range and reduce harmful emissions. However, the production, storage, and distribution of hydrogen pose substantial technical and economic challenges. Liquid hydrogen requires cryogenic storage and specialized infrastructure, which are currently limited. The high cost of green hydrogen production also limits its competitiveness with traditional fuels. Overcoming these challenges will require technological advancements, economies of scale, and supportive government policies.

Biofuels, derived from renewable feedstocks, offer a sustainable alternative to conventional jet fuels without requiring significant modifications to existing aircraft engines. The use of biofuels, such as biodiesel, can reduce CO_2 emissions and decrease the aviation industry’s environmental impact. The case study on the PZL M-28 Bryza aircraft showed that while biodiesel can reduce emissions, it also leads to higher fuel consumption and operational costs due to its lower calorific value compared to Jet A fuel. The cost-effectiveness of biofuels remains a challenge, and further advancements in biofuel production technology are necessary to make them a viable option for widespread use in aviation.

The transition to alternative energy sources in aviation is imperative for achieving environmental sustainability and reducing the sector’s carbon footprint. Each alternative energy source–batteries, hydrogen, and biofuels has its unique advantages and challenges. Batteries offer the potential for zero-emission flights but require significant improvements in energy density and infrastructure. Hydrogen promises high energy efficiency and clean emissions but faces hurdles in production and storage. Biofuels provide a near-term solution for reducing emissions but need further technological advancements to become economically viable.

The successful integration of these alternative fuels into the aviation industry will require collaborative efforts from industry stakeholders, government bodies, and research institutions. Continued research, technological innovation, and supportive policies are essential to overcoming the current limitations and fully realizing the potential of these alternative energy sources. As the aviation industry moves towards a more sustainable future, these alternative fuels will play a crucial role in reducing environmental impact and enhancing the efficiency and sustainability of air transport.

BIBLIOGRAPHY

Barkakaty B., Sumpter B.G., Ivanov I.N., Potter M.E., Jones Ch.W., Lokitz B.S., 'Emerging Materials for Lowering Atmospheric Carbon.' Environmental Technology & Innovation, 2017. https://doi.org/10.1016/j.eti.2016.12.001.

Baroutaji A., Wilberforce T., Ramadan M., Ghani Olabi A., 'Comprehensive Investigation on Hydrogen and Fuel Cell Technology in the Aviation and Aerospace Sectors.' Renewable and Sustainable Energy Reviews, 2019. https://doi.org/10.1016/j.rser.2019.02.022.

Baxter G., 'The Use of Aviation Biofuels as an Airport Environmental Sustainability Measure: The Case of Oslo Gardermoen Airport.' Mad - Magazine of Aviation Development 8, no. 1 (2020): 6–17. https://doi.org/10.14311/mad.2020.01.01.

Cheng F., Chen J., 'Metal–Air Batteries: From Oxygen Reduction Electrochemistry to Cathode Catalysts.' Chemical Society Reviews, 2012. https://doi.org/10.1039/c1cs15228a.

Choi Y., Bae Kim H., 'Analysis of Solar Energy Utilization Effect of Air-Based Photovoltaic/Thermal System.' Energies, 2021. https://doi.org/10.3390/en14248586.

Corlu C.G., de la Torre R., Serrano-Hernández A., Juan Á.A., Faulín J., 'Optimizing Energy Consumption in Transportation: Literature Review, Insights, and Research Opportunities.' Energies, 2020. https://doi.org/10.3390/en13051115.

Fuglestvedt J.S., Lund M.T., Kallbekken S., Samset B.H., Lee D.S., 'A 'Greenhouse Gas Balance' for Aviation in Line With the Paris Agreement.' Wiley Interdisciplinary Reviews Climate Change, 2023. https://doi.org/10.1002/wcc.839.

Gegg P.K., Budd L., Ison S., 'Stakeholder Views of the Factors Affecting the Commercialization of Aviation Biofuels in Europe.' International Journal of Sustainable Transportation 9, no. 8 (2015): 542–50. https://doi.org/10.1080/15568318.2013.825824.

Girardi J.C., Bariccatti R.A., Melegari de Souza S.N., Amaral C.Z., Carmen Guedes L.B., Baumi J., Bertosse C.M., 'Potential of Babassu Biofuels Use as Aviation Fuel.' Research Society and Development 11, no. 1 (2022): e51911125226. https://doi.org/10.33448/rsd-v11i1.25226.

Izdebski M., Jacyna-Gołda I., Gołda P., 'Minimisation of the Probability of Serious Road Accidents in the Transport of Dangerous Goods.' Reliability Engineering & System Safety 217 (2022): 108093.

Jones Ch.W., 'CO2 Capture From Dilute Gases as a Component of Modern Global Carbon Management.' Annual Review of Chemical and Biomolecular Engineering, 2011. https://doi.org/10.1146/annurev-chembioeng-061010-114252.

Lackner K.S., Brennan S., Matter J.M., Alissa Park A.-H., Wright A., van der Zwaan B., 'The Urgency of the Development of CO ₂ Capture From Ambient Air.' Proceedings of the National Academy of Sciences, 2012. https://doi.org/10.1073/pnas.1108765109.

Nygren E., Aleklett K., Höök M., 'Aviation Fuel and Future Oil Production Scenarios.' Energy Policy, 2009. https://doi.org/10.1016/j.enpol.2009.04.048.

Piranti M., 'The Impact of Fuel Price Fluctuation and Macroeconomic Variables to Airlines Performance.' Turkish Journal of Computer and Mathematics Education (Turcomat), 2021. https://doi.org/10.17762/turcomat.v12i3.2210.

Schmidt P., Batteiger V., Roth A., Weindorf W., Raksha T., 'Power-to-Liquids as Renewable Fuel Option for Aviation: A Review.' Chemie Ingenieur Technik, 2018. https://doi.org/10.1002/cite.201700129.

Seiple T., 'Cost-Effective Opportunities to Produce Sustainable Aviation Fuel From Low-Cost Wastes in the U.S.' Acs Sustainable Chemistry & Engineering, 2023. https://doi.org/10.1021/acssuschemeng.3c02147.

Singh V., Kumar Sharma S., 'Evolving Base for the Fuel Consumption Optimization in Indian Air Transport: Application of Structural Equation Modeling.' European Transport Research Review, 2014. https://doi.org/10.1007/s12544-014-0134-4.

Treanor S.D., Simkins B.J., Rogers D.A., Carter D.A., 'Does Operational and Financial Hedging Reduce Exposure? Evidence From the U.S. Airline Industry.' Financial Review, 2014. https://doi.org/10.1111/fire.12029.

Trinh J., Harahap F., Fagerström A., Hansson J., 'What Are the Policy Impacts on Renewable Jet Fuel in Sweden?' Energies, 2021. https://doi.org/10.3390/en14217194.

Turner P.A., Hoon Lim S., 'Hedging Jet Fuel Price Risk: The Case of U.S. Passenger Airlines.' Journal of Air Transport Management, 2015. https://doi.org/10.1016/j.jairtraman.2015.02.007.

Wise M., Muratori M., Kyle P., 'Biojet Fuels and Emissions Mitigation in Aviation: An Integrated Assessment Modeling Analysis.' Transportation Research Part D Transport and Environment, 2017. https://doi.org/10.1016/j.trd.2017.03.006.

Yakovlieva A., Сергій Валерійович Бойченко, Vasyl Boshkov, Lukas Korba, and Marián Hocko. 'Experimental Study of Physical-Chemical Properties of Advanced Alcohol-to-Jet Fuels.' Aviation, 2023. https://doi.org/10.3846/aviation.2023.18564.

Yin K., 'A Study of Carbon Dioxide Emissions Reduction Opportunities for Airlines on Australian International Routes,' n.d. https://doi.org/10.14264/uql.2017.688.

Zhang X., Wang X., Qiang Guan Z., Fang J., Sui R., Pei J., Qin Y., Wei D., Zhu W., Zhuang Z., 'An Ultrastable Rechargeable Zinc–Air Battery Using a Janus Superwetting Air Electrode.' Acs Applied Materials & Interfaces, 2022. https://doi.org/10.1021/acsami.2c14657.

Zhao Y., Ding H., Lin X., Li L., Liao W., Liu Y., 'Carbon Emissions Peak in the Road and Marine Transportation Sectors in View of Cost-Benefit Analysis: A Case of Guangdong Province in China.' Frontiers in Environmental Science, 2021. https://doi.org/10.3389/fenvs.2021.754192.

Ziółkowski J., Żurek J., Małachowski J., Oszczypała M., Szkutnik-Rogoż J., 'Method for Calculating the Required Number of Transport Vehicles Supplying Aviation Fuel to Aircraft during Combat Tasks.' Sustainability 14, no. 3 (January 2022): 1619. https://doi.org/10.3390/su14031619.