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PEST- AND SNW-ANALYSIS OF THE USE OF LIQUID HYDROGEN AS A MOTOR FUEL IN AVIATION

Abstract. *This article conducts a comprehensive PEST (Political, Economic, Social, Technological) and SNW (Strengths, Neutrals, Weaknesses) analysis on adopting liquid hydrogen as a motor fuel in the aviation industry. The urgency for sustainable aviation fuels is accentuated by the escalating environmental concerns and the aviation sector's significant carbon footprint. Liquid hydrogen, recognized for its high energy density and zero carbon emissions at the point of use, emerges as a promising alternative to conventional aviation fuels. Through a PEST analysis, the article examines the multifaceted external factors influencing the feasibility of liquid hydrogen in aviation, including supportive policies, economic considerations, societal attitudes towards green aviation, and the technological challenges and advancements in hydrogen fuel technologies. The SNW analysis delves into the intrinsic aspects of liquid hydrogen's application in aviation, highlighting its strengths such as environmental benefits and renewable production potential, its neutral factors that may neither significantly impede nor accelerate its adoption, and its weaknesses including storage and transportation challenges. The article concludes with strategic recommendations to mitigate the identified deficiencies, leverage strengths, and transform neutrals into opportunities for the widespread adoption of liquid hydrogen in aviation. This study aims to provide stakeholders in the aviation sector with insightful analyses to navigate the complexities of introducing liquid hydrogen as a sustainable aviation fuel, contributing to the broader goal of achieving carbon-neutral aviation.*
Keywords: transport, aviation, liquid hydrogen, motor fuel, sustainable aviation fuels, energy efficiency, electrical equipment.

1. Introduction

Civil aviation is traditionally considered a modern and progressive mode of transport, and it is no accident that it always occupies a prominent place in the development of the transport system in most countries of the world. The appearance of new comfortable, high-speed, and economical airplanes on the airlines requires the availability and development of ground facilities (aviation ground equipment) that allow for prompt and high-quality technical and commercial maintenance of airfields.

Among the wide range of samples of aviation ground equipment (AGE), special machines designed for maintenance of aircraft occupy a prominent place, since the technical condition of the aircraft is a decisive factor in ensuring the regularity and safety of flights.

One of the main tasks of civil aviation is the commercial air transportation of passengers, mail and cargo. In order to implement the above task, a significant number of different types of AGE are operated at airports.

Since the quality and cleanliness of the airfield significantly affect the level of safety and regularity of flights, there is a separate group of AGE – airfield equipment designed for operational maintenance of airfield surfaces at any time of the year.

Even a brief analysis of the main areas of application of aviation ground equipment, depending on the volume of passenger and cargo transportation at a specific airport, the area and configuration of the airfield, and other factors, shows the need to involve in operation a significant number of AGE, the values of which are in a wide range – from hundreds to thousands of units.

2. Methods and materials

2.1. *Газотурбінні електростанції*

It is quite obvious that the number of special vehicles at the airport directly depends on the intensity of aircraft take-offs and landings, each of which is accompanied by a complex of technological processes for ground maintenance of aircraft on the apron [1].

There is a formula for determining the total number of AGEs related to the schedule of aircraft traffic, according to which the optimal number of special vehicles is determined depending on the daily irregularity of air traffic:

$$n = \frac{C_{gen} K_{di} K_{serv} T_c m}{6 T_{daily} K_{tr}}, \quad (1)$$

where C_{gen} – is the total number of aircraft take-offs and landings per day; K_{di} – is the coefficient of daily unevenness of aircraft take-offs; K_{serv} – service factor:

$$K_{serv} = 1 + \frac{C_{act}}{C_{gen}}, \quad (2)$$

where C_{act} – is the actual number of aircraft take-offs per day; T_c – is the cycle time of maintenance of the aircraft by a special vehicle of a certain functional purpose; m – the number of special vehicles of a certain type that are simultaneously used for ground maintenance of aircraft; T_{daily} – duration of operation of a special machine of a certain functional purpose per day; K_{tr} – is the coefficient of technical readiness of AGE.

3. Results

The amount of AGE for aircraft ground handling can also be determined graphically, using appropriate nomograms.

According to statistics, about 85–90% of airport special vehicles use internal combustion engines (gasoline or diesel) as a power plant to drive the base chassis and special equipment, which cannot help but affect the level of environmental safety in airport and near-airport areas [2].

Undoubtedly, the level of environmental pollution in airports largely depends on acoustic loads and harmful emissions created by aircraft engines, but we cannot forget about the environmental risks arising from the operation of a large number of AGEs [3].

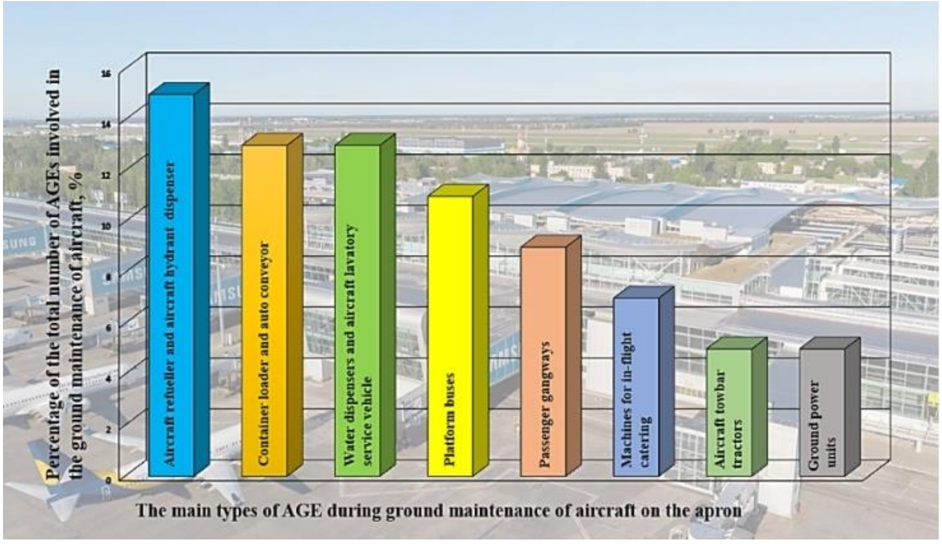

Figure 1. Distribution of the main types of AGE according to their quantity at ground level aircraft maintenance

Based on the analysis of the flight operation manuals of the most common types of civil aviation aircraft, technological schedules for aircraft ground maintenance, based on the application of a statistical method and the method of expert evaluations, the segment of those types of AGE, the number of which is the maximum on the passenger and cargo platforms of the airport at the ground level, was determined aircraft maintenance.

Quantitative and qualitative analysis of the situation with the use of aviation ground equipment for operational maintenance of airfields requires separate studies and was not considered in the framework of writing this article. Although it is absolutely obvious that the level of environmental risks from the use of airfield machines is also significant.

The histogram shows the quantitative indicators of the types of aviation ground equipment most common on the platform as a percentage of the total number of special vehicles involved in technological processes for operational maintenance of aircraft (Fig. 1).

In addition to purely quantitative indicators regarding different types of anti-aircraft vehicles, it is important to find out the value of the total duration of their stay on the platforms, taking into account the time of movement from the operational parking lot of special vehicles to the buffer zone of aircraft maintenance, positioning near the aircraft, bringing special equipment into working position, using anti-aircraft vehicles as intended, bringing them to transport position and movement in the reverse direction - to the operational parking lot (Fig. 2).

The above analysis regarding the quantitative assessment of various types of aviation ground equipment and the duration of their use with working gasoline (diesel) engines during aircraft ground maintenance is, in our opinion, decisive for determining the priority directions for the modernization of AGE power plants in order to improve the environmental situation on airport aprons.

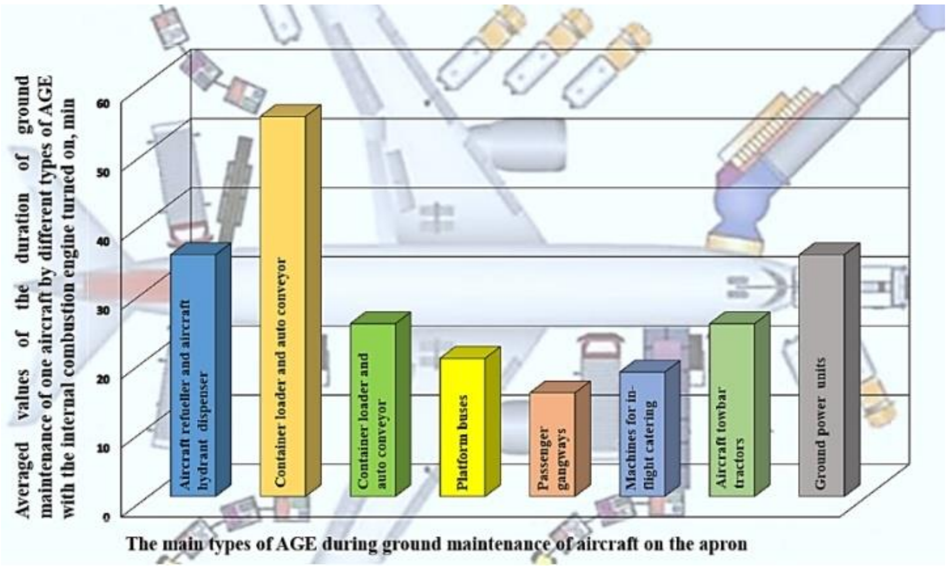

Figure 2. Distribution of the main types of AGE according to the average duration of their use with the internal combustion engines turned on during ground maintenance of one aircraft

First of all, we are talking about the need for the production (modernization) of AGE types with electric motors as the main sources of energy, which are maximally represented on the platform, which are necessary for the movement of special vehicles and their use as intended.

One of the promising areas of greening of the AGE design is the introduction of so-called hydrogen engines, which differ from traditional electric ones by a fundamentally different process of generating electric current in chemical reactors. However, even as a combustible gas, hydrogen has high performance (Table 1, 2). Moreover, technologies for production and storage of liquid/gaseous hydrogen are constantly being improved.

Table 1. Thermophysical characteristics of hydrogen

Flammable gas	Lower heat of combustion (Q_l), kJ/m³ (kcal/m³)	Higher heat of combustion (Q_h), kJ/m³ (kcal/m³)	Q_h/Q_l, %	Ignition temperature, °C	Ignition limits in mixture with air, %	Calorimeter combustion temperature, °C	Norm. flame propagation speed*, m/sec
CH_4	35739 (8550)	39500 (9450)	111	645	5–15	2211	0.28
H_2	10800 (2580)	12767 (3054)	118	510	3.3–81.5	2380	1.6

*Other sources give values for CH_4: 0.37; for H_2: 2.7–4.8 m/sec.

Table 2. Properties comparison between traditional aviation kerosene and liquid hydrogen

Property/Feature	Unit	Jet A-1	Liquid hydrogen
Volumetric energy density	[MJ/L]	33	10.1
Gravimetric energy density	[MJ/kg]	43.2	120
Storage temperature	[K]	Ambient	20

The transition to sustainable aviation fuels (SAFs) is a crucial step towards achieving global environmental sustainability goals, particularly in reducing the aviation industry's substantial carbon footprint. Aviation is a significant contributor to global CO2 emissions, and as air travel demand continues to grow, the urgency to find environmentally friendly alternatives to conventional jet fuels becomes more pressing. Sustainable aviation fuels offer a promising solution to this challenge, with liquid hydrogen emerging as a particularly compelling option (Table 3).

Table 3. Volume-Mass Characteristics of Various Hydrogen Storage Systems Compared to Gasoline

Indicator	Gasoline	Compressed Hydrogen	Liquid Hydrogen	MgH2 Hydride
Fuel mass, kg	53.5	13.4	13.4	18.1
Fuel volume, m³	0.07	1.08	0.19	0.23
Tank mass, kg	13.06	136.1	181	45.4
Tank volume, m³	0.08	1.83	0.28	0.25
Total system mass, kg	67	137.4	195	227

Liquid hydrogen, when used as a fuel (Table 4), produces water vapor as its primary byproduct, eliminating carbon emissions during flight. This starkly contrasts with traditional aviation fuels that release significant amounts of CO2 and other pollutants. Transitioning to liquid hydrogen can drastically reduce the aviation sector's impact on air quality and climate change. Liquid hydrogen has a high energy density by weight, making it an efficient fuel choice for aviation. Although it requires more volume per unit of energy compared to conventional fuels, its lightweight nature allows for greater efficiency in flight, potentially leading to longer ranges and reduced fuel consumption. Hydrogen can be produced from various sources, including water via electrolysis, which can be powered by renewable energy sources such as solar or wind. This process allows for the production of liquid hydrogen without emitting CO2, aligning with global efforts to transition to a more sustainable and circular energy economy. Investing in liquid hydrogen as an aviation fuel drives technological innovation and infrastructure development (Fig. 3). It opens up new markets and opportunities for economic growth, particularly in regions with abundant renewable energy resources.

The development of a hydrogen economy can create jobs, stimulate technological advancements, and reduce dependency on oil and gas reserves. Liquid hydrogen's role extends beyond aviation; it is a versatile energy carrier that can be integrated into broader energy systems for storage, transportation, and decarbonization efforts across industries. This compatibility enhances its potential as a cornerstone of future sustainable energy ecosystems. Despite its potential, the transition to liquid hydrogen in aviation faces challenges, including the need for significant infrastructure investments, technological advancements in storage and fuel cell efficiency, and ensuring safety in handling and transportation. Addressing these challenges requires coordinated efforts among governments, industry stakeholders, and the research community [4].

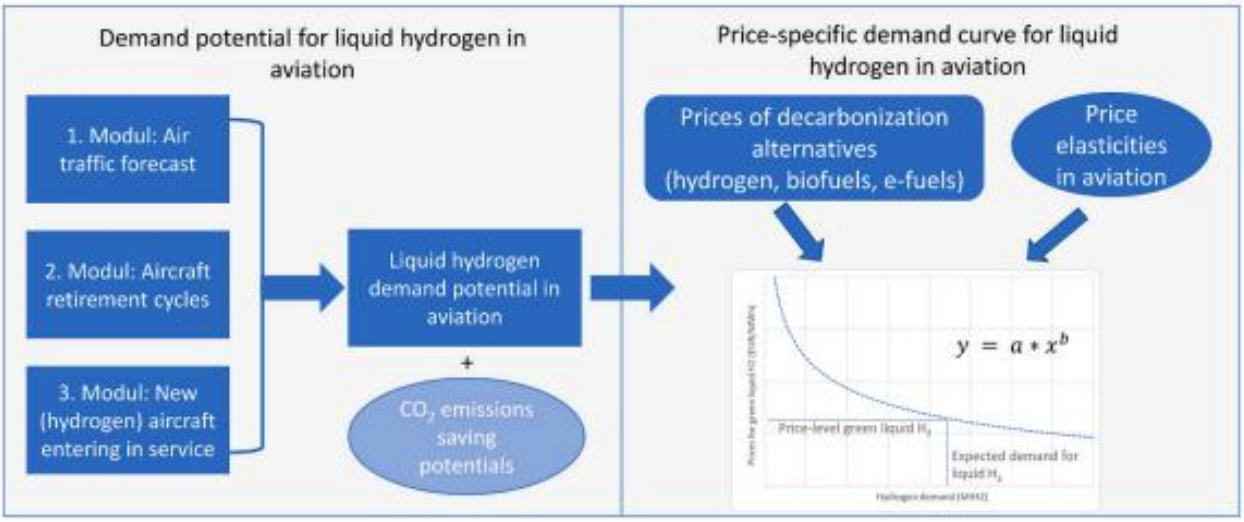

Figure 3. Demand characteristics for liquid hydrogen in avaition

In summary, transitioning to sustainable aviation fuels (SAF), with a focus on liquid hydrogen, represents a critical pathway towards decarbonizing the aviation sector and achieving broader environmental and sustainability goals. While obstacles remain, the benefits of liquid hydrogen–ranging from its environmental impact to its role in fostering economic and technological innovation–underscore its potential as a transformative solution for sustainable aviation.

Table 4. Properties of Hydrogen and Some Comparable Substances

	Valid at		Hydrogen[1]	Methane	Propane	Heptane[3]
Boiling point	1.013 bara	K	20.4	111.6	231.1	371.5
Critical temperature		K	33.19	119.6	396.8	540.4
Critical pressure		bara	13.15	46.0	42.4	27.5
Density of liquid	Boiling point	kg/m^3	70.8	422.5	580.7	680.4
Heat of vaporization	Boiling point	kJ/kg	445.6	510.4	427.8	317.0
Density of gas	Boiling point	kg/m^3	1.338	1.818	2.419	3.29
Density of gas	1.013 bara 0 °C	kg/m^3	0.090	0.717	2.011	4.46
Specific heat, Cp	1.013 bara 0 °C	kJ/kg K	14.19	2.19	1.56	1.705
Specific heat, Cv	1.013 bara 0 °C	kJ/kg K	10.06	1.67	1.35	N/A
Thermal conductivity	1.013 bara 0 °C	W/m K	0.1682	0.0305	N/A	0.01886[6]
Diffusion coefficient (in air)	1.013 bara 20 °C	cm^2/S	0.69	0.22	0.12	0.05
Limits of flammability[2]	1.013 bara 20 °C	Vol. %	4.0–75.0	5.0–15.4	2.1-9.5	1.11–6.7
Auto ignition temperature[2]	1.013 bara	°C	560	595	470	215
Minimum ignition energy[2]	1.013 bara 20 °C	mJ	0.019	0.28	0.26	0.22
Theoretical temperature of flame[2]	1.013 bara	°C	2045	1875	2040	2200

1. Normal hydrogen (75 % ortho and 25 % para)
2. Combustion with air
3. As a representative for gasoline
4. At 0 °C
5. Vapour at 25 °C
6. Vapour at 100 °C

Conversion: 1 bar = 105 Pa

The essay aims to comprehensively explore the viability of liquid hydrogen as a motor fuel in aviation, employing two distinct analytical frameworks: PEST-analysis and SNW-analysis. Through the PEST-analysis, the essay will delve into the Political, Economic, Social, and Technological dimensions that influence the adoption and implementation of liquid hydrogen in the aviation sector. This approach provides a broad understanding of the external factors that could facilitate or hinder the transition to liquid hydrogen as an aviation fuel, including regulatory environments, economic incentives, societal perceptions, and technological readiness. Simultaneously, the SNW-analysis will offer an internal perspective, focusing on the inherent Strengths, Neutrals, and Weaknesses of liquid hydrogen as a fuel choice. This analysis aims to identify the intrinsic advantages that liquid hydrogen offers, such as its potential for zero carbon emissions and high energy density, alongside the challenges it faces, including storage and transportation logistics. Neutrals, a unique aspect of this analysis, will highlight factors currently seen as neither strengths nor weaknesses but could shift in importance with changes in technology, market demands, or regulatory landscapes.

By integrating findings from both PEST (Table 5) and SNW-analyses (Table 6), the essay will provide a holistic assessment of liquid hydrogen's potential role in advancing sustainable aviation. This dual-framework approach enables a nuanced exploration of both the external influences on and internal characteristics of liquid hydrogen fuel, offering insights into its practical viability and strategic importance for the future of aviation.

1) Political: The political landscape plays a critical role in the adoption and implementation of SAFs, including liquid hydrogen.

（1）Government Policies: National governments around the world are increasingly recognizing the need for cleaner aviation fuels to meet carbon reduction targets. Policies that encourage the research, development, and commercialization of SAFs, including liquid hydrogen, are crucial. These can take the form of direct funding for research, tax incentives for companies investing in SAF technology, or mandates requiring a certain percentage of fuel used by airlines to be sustainable.

（2）Subsidies and Financial Incentives: Subsidies and other financial incentives are essential tools to offset the higher initial costs associated with transitioning to SAFs like liquid hydrogen. By providing economic incentives to airlines, fuel producers, and infrastructure developers, governments can lower the barrier to entry and accelerate the adoption of liquid hydrogen as an aviation fuel.

（3）International Agreements: Climate change and environmental sustainability are global challenges that require international cooperation. International agreements, such as the Paris Agreement, set broad goals for reducing greenhouse gas emissions, but specific initiatives like the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) directly target aviation emissions. Such agreements can provide a framework for global action and encourage countries to adopt policies that support SAFs, including liquid hydrogen.

（4）Regulatory Frameworks: Effective regulatory frameworks are essential to ensure the safe production, storage, transportation, and use of liquid hydrogen in aviation. Regulations need to address safety concerns, set standards for fuel quality and infrastructure, and ensure compatibility with existing systems. Governments play a key role in developing these frameworks in consultation with industry stakeholders and international bodies.

By addressing these political factors, the aviation industry can create a supportive environment for the introduction and scaling of liquid hydrogen as a sustainable fuel option. The success of this transition will depend not only on technological advancements and economic viability but also on the political will and cooperation at both national and international levels.

Table 5. PEST Analysis of liquid hydrogen's potential role in advancing sustainable aviation

Groups of Factors	Events/Factors	Threats/Possibilities	Likelihood of an Event or Manifestation of a Factor	The Importance of a Factor or Event	Influence on the Organization	Action Program
Political [5]	Government policies, subsidies, international agreements, regulatory frameworks	Regulatory changes, international policy shifts	High likelihood due to global climate commitments	Crucial for the adoption of SAFs like liquid hydrogen	Direct impact on strategy and operations	Develop policy strategies, engage in advocacy
Economic [6]	Cost implications, investment requirements	Market volatility, technological advancements	Dependent on market forces and technological progress	Significant for economic viability and sustainability	Affects financial stability and investment decisions	Plan for economic shifts, invest in R&D
Social [7]	High energy density, zero carbon emissions at point of use, potential for renewable sourcing	Public perception, environmental advocacy	Increasing as public awareness and environmental concerns grow	Essential for social acceptance and regulatory approval	Influences company image and market position	Educate the public, promote environmental benefits
Technological [8][9]	Advanced cryogenic storage tanks and fuel cell engines in development stages	Potential delays in technology commercialization	High, as technologies are at a tipping point and close to practical solutions	Critical for the widespread use of liquid hydrogen in aviation	Direct impact on operational capabilities and market readiness	Invest in R&D, prepare for integration of new technologies

2) Economic: The economic dimension of adopting liquid hydrogen as a motor fuel in aviation encompasses several critical factors, including cost implications, investment requirements, and potential economic benefits.

（1）Cost Implications

• Production Costs: Currently, the production cost of liquid hydrogen is higher than that of conventional jet fuel due to the energy-intensive processes required for hydrogen liquefaction and the costs associated with renewable energy sources. Economies of scale and technological advancements could reduce these costs over time.

• Infrastructure Development: Significant investment is needed to develop the infrastructure for producing, storing, and distributing liquid hydrogen. This includes hydrogen production facilities, storage tanks at airports, and refueling systems that can handle liquid hydrogen's cryogenic properties.

（2）Investment Requirements

• Research and Development (R&D): Investing in R&D is crucial for improving hydrogen production technologies, increasing efficiency, and developing safer, more cost-effective storage and distribution methods.

• Capital Expenditure (CapEx): The aviation industry and governments must allocate substantial capital expenditure for infrastructure development, including retrofitting or building new aircraft capable of using liquid hydrogen.

• Training and Safety Measures: Additional investments in training for handling and using liquid hydrogen safely, along with implementing robust safety measures, are essential due to its flammability and the need for cryogenic storage.

（3）Economic Benefits

• Energy Security and Independence: Liquid hydrogen can reduce dependency on oil imports, enhancing energy security and potentially stabilizing fuel costs in the long term due to the widespread availability of water as a source for hydrogen production.

• Job Creation: The shift to liquid hydrogen is expected to create jobs in hydrogen production, infrastructure development, maintenance, and the broader renewable energy sector.

• Environmental Taxation and Compliance Costs: Adopting liquid hydrogen could reduce the aviation industry's exposure to environmental taxes and compliance costs associated with carbon emissions. This shift aligns with increasing regulatory pressure to decrease environmental footprints.

• Market Opportunities: As global demand for sustainable travel options grows, early adopters of liquid hydrogen technology may benefit from increased market share and a positive brand image among environmentally conscious consumers.

In summary, while the transition to liquid hydrogen as an aviation fuel presents significant economic challenges, including high initial costs and substantial investment in infrastructure and technology, it also offers long-term economic benefits. These benefits include energy independence, job creation, reduced environmental compliance costs, and the potential to lead in a growing market for sustainable aviation solutions. Strategic investments and policy support are essential to realize these benefits and make liquid hydrogen a viable economic option for the aviation industry.

3) **Social:** The social dimension of transitioning to liquid hydrogen as a motor fuel in aviation encompasses public perception, environmental advocacy, and the push towards greener aviation technologies.

(1) Public Perception

• Environmental Awareness: Increasing awareness of climate change and environmental issues has led to a growing demand from the public for more sustainable practices in all sectors, including aviation. Consumers are more inclined to support airlines that demonstrate a commitment to reducing their environmental impact.

• Safety Concerns: Public perception of hydrogen's safety, given its flammability and association with historical accidents, may present challenges. Addressing these concerns through transparent communication and demonstrating strict safety protocols is essential.

• Willingness to Pay: Research indicates a segment of consumers is willing to pay a premium for flights that use sustainable fuels, reflecting a shift in values towards environmental responsibility. However, this willingness varies across demographics and regions.

(2) Environmental Advocacy

• NGOs and Environmental Groups: Non-governmental organizations and environmental advocacy groups play a vital role in pushing for greener aviation technologies. They raise awareness, lobby for policy changes, and can influence public opinion and consumer behavior towards supporting sustainable aviation solutions like liquid hydrogen.

• Corporate Social Responsibility (CSR): Companies are increasingly judged on their environmental footprint, leading to a stronger emphasis on CSR. Airlines and fuel producers investing in liquid hydrogen can enhance their brand image and fulfill their CSR objectives, aligning with broader environmental goals.

(3) Social Push Towards Greener Aviation Technologies

• Innovation and Collaboration: There is a social drive for innovation and collaboration between industries, governments, and research institutions to develop and implement greener aviation technologies. Public support for such initiatives can accelerate their adoption.

• Education and Awareness: Educating the public about the benefits and realities of sustainable aviation fuels, including liquid hydrogen, is crucial for garnering support. Awareness campaigns can demystify the technology and highlight its potential to reduce aviation’s carbon footprint.

• Social Media and Influencer Advocacy: Social media platforms and influencers can significantly impact public opinion and behavior. Leveraging these channels to promote the benefits of liquid hydrogen and sustainable aviation practices can help shift consumer preferences and demand.

In conclusion, the social aspect is pivotal in the transition to liquid hydrogen for aviation fuel. Building positive public perception, coupled with strong environmental advocacy and a societal push for sustainability, can overcome barriers and accelerate the adoption of liquid hydrogen. Effective communication, education, and engagement strategies are key to navigating the social landscape and ensuring broad support for this transformative shift towards greener aviation technologies.

Table 6. SWN Analysis of liquid hydrogen's potential role in advancing sustainable aviation

Strategic positions and characteristics	Qualitative assessment		
	S	**N**	**W**
High Energy Density	√	×	×
ZeroCarbon Emissions at Point of Use	√	×	×
Potential for Renewable Sourcing	√	×	×
Existing Infrastructure Compatibility	×	√	×
Global Hydrogen Production Capacities	×	√	×
Technological Readiness Levels	×	√	×
Regulatory and Safety Standards	×	√	×
Public Awareness and Perception	×	√	×
Cryogenic Storage Requirements	×	×	√
Safety Concerns	×	×	√
Lack of Widespread Hydrogen Refueling Infrastructure	×	×	√
Economic Viability	×	×	√
Technological Maturity	×	×	√

1) Strengths: The strengths of liquid hydrogen as a motor fuel in aviation are compelling, particularly when considering its potential to significantly reduce the environmental impact of air travel.

(1) High Energy Density

Liquid hydrogen boasts a high energy density by weight, making it one of the most efficient fuels available. This attribute translates into potentially longer flight ranges and reduced weight compared to conventional jet fuels, offering significant operational efficiencies for airlines.

(2) Zero Carbon Emissions at Point of Use

One of the most significant strengths of liquid hydrogen is its clean combustion process, which emits only water vapor and no CO_2. This characteristic makes it an ideal solution for drastically reducing the aviation industry's carbon footprint, aligning with global efforts to combat climate change.

(3) Potential for Renewable Sourcing

Hydrogen can be produced from water through electrolysis, an environmentally friendly process, especially when powered by renewable energy sources like wind, solar, or hydroelectric power. This renewable sourcing capability positions liquid hydrogen as a sustainable aviation fuel that can contribute to a circular economy and decrease dependency on fossil fuels.

These strengths make liquid hydrogen a highly attractive option for the future of aviation fuel, promising a sustainable pathway that addresses both operational efficiencies and environmental responsibilities. The transition to liquid hydrogen in aviation could revolutionize the industry, offering a clean, efficient, and renewable energy source that meets the growing demand for sustainable travel solutions.

2) Neutrals: The neutrals in the context of adopting liquid hydrogen as a motor fuel in aviation encompass factors that, in their current state, neither significantly propel nor impede its adoption. These elements are crucial in understanding the balanced landscape within which liquid hydrogen operates.

(1) Existing Infrastructure Compatibility

Current aviation fueling infrastructure is predominantly designed for conventional jet fuels. While this presents a challenge for integrating liquid hydrogen, some existing infrastructure elements might be repurposed or adapted with moderate modifications. The neutral stance here reflects the balance between the need for significant investment in new infrastructure and the potential for leveraging certain existing assets.

(2) Global Hydrogen Production Capacities

The current global capacity for hydrogen production is primarily oriented towards industrial applications, not specifically aviation. While this capacity does not directly facilitate the rapid adoption of liquid hydrogen in aviation, it establishes a foundation upon which to build and scale up. The neutral impact stems from the fact that increasing production for aviation needs is feasible but requires targeted investment and development.

(3) Technological Readiness Levels

Many technologies critical for the widespread use of liquid hydrogen in aviation, such as advanced cryogenic storage tanks and fuel cell engines, are in advanced stages of development but not yet fully commercialized. These technologies are at a tipping point, where significant advancements could rapidly shift them from neutral to strengths, accelerating adoption. Their current status as neutrals reflects the ongoing research and development efforts that are close to yielding practical solutions.

(4) Regulatory and Safety Standards

Regulatory and safety standards for liquid hydrogen use in aviation are under development, with existing regulations primarily focused on ground applications. The neutrality lies in the anticipation of these standards becoming either facilitators or barriers based on how they evolve to address the unique challenges of aviation.

(5) Public Awareness and Perception

Public awareness of liquid hydrogen's potential is increasing, yet knowledge and understanding of its application in aviation specifically remain limited. This neutral factor highlights the opportunity to influence public perception positively through education and advocacy, which could support adoption in the future.

These neutral factors represent a state of equilibrium in the transition towards liquid hydrogen as a sustainable aviation fuel. Their evolution into strengths or weaknesses will significantly depend on strategic decisions, investments, and developments in the coming years. Addressing these neutrals effectively could pave the way for liquid hydrogen to become a cornerstone of sustainable aviation.

3) Weaknesses: The transition to liquid hydrogen as an aviation fuel, while promising, is not without its challenges.

(1) Cryogenic Storage Requirements

Liquid hydrogen must be stored at extremely low temperatures (mines 253 °C or -423 °F) to remain in liquid form, necessitating specialized cryogenic storage solutions. These requirements present both technical challenges and significant costs for storage infrastructure development, both on the ground and onboard aircraft.

(2) Safety Concerns

Hydrogen's high flammability and the need for cryogenic storage raise safety concerns. Ensuring safe handling, storage, and refueling operations requires stringent safety protocols and systems, increasing the complexity and cost of operations. Public perception of hydrogen's safety, influenced by historical incidents, also poses a challenge, requiring extensive safety demonstrations and education efforts.

(3) Lack of Widespread Hydrogen Refueling Infrastructure

Currently, there is a significant gap in the hydrogen refueling infrastructure needed to support widespread adoption of liquid hydrogen in aviation. Building this infrastructure requires substantial investment and coordination across various stakeholders, including airports, fuel suppliers, and governments. The absence of a comprehensive refueling network limits the operational feasibility of hydrogen-powered aircraft, particularly for long-haul and international flights.

(4) Economic Viability

The shift to liquid hydrogen involves high initial costs, not only for developing and deploying new aircraft technologies and fuel systems but also for establishing the production and distribution infrastructure. These economic barriers may slow adoption rates, especially in a cost-sensitive industry like aviation.

(5) Technological Maturity

While significant progress has been made, some technologies critical for the widespread use of liquid hydrogen in aviation, such as fuel cells and cryogenic fuel tanks, are still under development. Integrating these technologies into commercial aircraft design and operation poses engineering challenges that must be overcome.

Addressing these weaknesses is crucial for the successful adoption of liquid hydrogen as a sustainable aviation fuel. Solutions include advancing cryogenic technology, establishing rigorous safety protocols, incentivizing infrastructure development, and promoting technological innovation. Overcoming these challenges will require coordinated efforts from the aviation industry, governments, and research institutions, along with substantial investment in research, development, and infrastructure projects.

4. Conclusion

The exploration of liquid hydrogen as a motor fuel in aviation through PEST and SNW-analyses provides a comprehensive overview of its viability and challenges. Policies, subsidies, and international agreements are gradually aligning to support the transition to sustainable aviation fuels like liquid hydrogen, although regulatory frameworks are still evolving. The economic landscape presents both challenges and opportunities, including high initial costs for infrastructure and technology development, balanced by long-term benefits such as energy security and job creation. Public perception and environmental advocacy play crucial roles, with growing consumer demand for sustainable travel options and safety concerns that need addressing. Technological advancements are promising but require further development and commercialization to fully support the adoption of liquid hydrogen in aviation. The balance of strengths, neutrals, and weaknesses underscores the potential of liquid hydrogen in aviation while highlighting the need for targeted investments, policy support, and technological innovation. Overcoming the identified weaknesses and leveraging the neutrals will be key to unlocking liquid hydrogen's full potential as a sustainable aviation fuel. This holistic analysis through the PEST and SNW lenses provides valuable insights into strategic actions required to advance the adoption of liquid hydrogen, ensuring a sustainable future for aviation.

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PEST- ТА SNW-АНАЛІЗ ВИКОРИСТАННЯ РІДКОГО ВОДНЮ ЯК МОТОРНОГО ПАЛИВА В АВІАЦІЇ

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Анотація. *У цій статті проведено комплексний аналіз PEST (Political, Economic, Social, Technological – політичні, економічні, соціальні, технологічні) та SNW (Strengths, Neutrals, Weaknesses – сильні, нейтральні, слабкі сторони) щодо впровадження рідкого водню як моторного палива в авіаційній промисловості. Нагальна потреба в екологічно чистому авіаційному паливі посилюється зростаючими екологічними проблемами та значним вуглецевим слідом авіаційного сектору. Рідкий водень, відомий своєю високою енергетичною щільністю та нульовими викидами вуглецю в місці використання, стає багатообіцяючою альтернативою традиційним авіаційним паливам. За допомогою PEST-аналізу в статті розглядаються багатогранні зовнішні фактори, що впливають на можливість використання рідкого водню в авіації, включаючи політику підтримки, економічні міркування, ставлення суспільства до «зеленої» авіації, а також технологічні виклики і досягнення в галузі водневих паливних технологій. SNW-аналіз заглиблюється у внутрішні аспекти застосування рідкого водню в авіації, висвітлюючи його сильні сторони, такі як екологічні переваги та потенціал відновлюваного виробництва, нейтральні фактори, які можуть суттєво перешкоджати або прискорювати його впровадження, а також його слабкі сторони, включаючи проблеми зберігання і транспортування. Стаття завершується стратегічними рекомендаціями, спрямованими на пом'якшення виявлених слабких сторін, використання сильних сторін і перетворення нейтральних факторів на можливості для широкого впровадження рідкого водню в авіації. Це дослідження має на меті надати зацікавленим сторонам в авіаційному секторі глибокий аналіз, який допоможе зорієнтуватися в складнощах впровадження рідкого водню як сталого авіаційного палива, що сприятиме досягненню ширшої мети − переходу до вуглецево-нейтральної авіації.*

Ключові слова: транспорт, авіація, рідкий водень, моторне паливо, стале авіаційне паливо, енергоефективність, електрообладнання.

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