International Hydrogen Scientific Conference
Green Transformation

SUBCARPATHIAN HYDROGEN VALLEY

Pathways to Green Transformation

- Proceedings of The International Hydrogen Scientific Conference 2025

RZESZÓW, 2025

Redakcja naukowa:
Kamil Kucharski

OFICYNA WYDAWNICZA POLITECHNIKI RZESZOWSKIEJ

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Introduction

In the face of escalating challenges posed by climate change and the pressing need for energy transformation, the pursuit of sustainable and low-emission energy sources has become one of the top priorities of modern societies. Hydrogen, as a clean energy carrier, is gaining increasing importance in the context of global efforts to decarbonize industry, energy production, and transportation. Its potential both as a fuel of the future and a cornerstone of the modern energy economy was the central focus of "The International Hydrogen Scientific Conference: Green Transformation", held from April 14-16, 2025, at the Rzeszów University of Technology.

The aim of the conference was to integrate scientific, industrial, and institutional communities around the topics related to hydrogen technologies and their role in the ongoing energy transition. The event attracted a wide range of participants from experienced researchers and engineers to doctoral students, undergraduates, and representatives of business and public administration. Attendees had the opportunity to present the latest research findings, engage in interdisciplinary panel discussions, and establish scientific and industrial collaborations. This monograph is a direct outcome of the conference and contains twelve scientific articles, prepared in either Polish or English. The authors represent diverse academic and professional backgrounds from students and PhD candidates to researchers and industry experts.

The articles cover a broad spectrum of hydrogen-related topics: from production, storage, and transportation technologies to legal and regulatory frameworks, as well as practical applications in road and air transport, including the environmental benefits of reducing harmful emissions. The monograph is interdisciplinary in nature and presents a valuable contribution to the ongoing development of knowledge in the field of hydrogen technologies.

We hope that this publication will further contribute to the promotion and advancement of research into hydrogen as a key component of the green transformation and serve as a valuable source of inspiration for researchers, engineers, students, and policymakers shaping the future of the energy sector. The project was co-financed with funds from the state budget, granted by the Polish Minister of Science within the framework of the Excellent Science II Program.

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Kamil KUCHARSKI[1]

Wstęp

W obliczu narastających wyzwań związanych ze zmianami klimatycznymi oraz pilnej potrzeby transformacji energetycznej, poszukiwanie zrównoważonych i niskoemisyjnych źródeł energii stało się jednym z najważniejszych priorytetów współczesnych społeczeństw. Wodór jako nośnik czystej energii, zyskuje coraz większe znaczenie w kontekście globalnych działań na rzecz dekarbonizacji przemysłu, produkcji energii oraz transportu. Jego potencjał zarówno jako paliwa przyszłości, jak i podstawy nowoczesnej gospodarki energetycznej był głównym tematem „The International Hydrogen Scientific Conference: Green Transformation", która odbyła się w dniach 14-16 kwietnia 2025 roku na Politechnice Rzeszowskiej im. Ignacego Łukasiewicza.

Celem konferencji była integracja środowisk naukowych, przemysłowych i instytucjonalnych wokół zagadnień związanych z technologiami wodorowymi oraz ich rolą w trwającej transformacji energetycznej. Wydarzenie zgromadziło szerokie grono uczestników od doświadczonych naukowców i inżynierów, po doktorantów, studentów oraz przedstawicieli biznesu i administracji publicznej. Uczestnicy mieli okazję zaprezentować najnowsze wyniki badań, wziąć udział w interdyscyplinarnych panelach dyskusyjnych oraz nawiązać współpracę naukową i przemysłową. Niniejsza monografia stanowi bezpośredni rezultat konferencji i zawiera dwanaście artykułów naukowych przygotowanych w języku polskim lub angielskim. Ich autorami są przedstawiciele różnych środowisk akademickich i zawodowych od studentów i doktorantów, po badaczy oraz ekspertów z sektora przemysłowego.

Zawarte w publikacji artykuły obejmują szeroki zakres tematyczny związany z wodorem od technologii jego produkcji, magazynowania i transportu, poprzez zagadnienia prawne i regulacyjne, aż po praktyczne zastosowania w transporcie drogowym i lotniczym, w tym analizę korzyści środowiskowych wynikających z redukcji emisji szkodliwych substancji. Monografia ma charakter interdyscyplinarny i stanowi cenny wkład w rozwój wiedzy dotyczącej technologii wodorowych. Wyrażamy nadzieję, że niniejsza publikacja przyczyni się do dalszego promowania i rozwoju badań nad wodorem jako kluczowym elementem zielonej transformacji oraz będzie inspirującym źródłem wiedzy dla naukowców, inżynierów, studentów i osób kształtujących przyszłość sektora energetycznego. Projekt został dofinansowany ze środków budżetu państwa, przyznanych przez Ministra Nauki w ramach Programu Doskonała Nauka II.

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STRATEGIC AND FORWARD-LOOKING INVESTIGATIONS OF THE USE OF LIQUID HYDROGEN AS A LOW-CARBON FUEL IN AVIATION

The adoption of liquid hydrogen as a sustainable aviation fuel is critically examined in this chapter through a comprehensive PEST (Political, Economic, Social, Technological) and SNW (Strengths, Neutrals, Weaknesses) analysis. Recognizing the urgency driven by escalating environmental concerns and the aviation sector's substantial carbon footprint, the study explores the external enabling and hindering factors (PEST) alongside the intrinsic advantages and limitations (SNW) of liquid hydrogen utilization. The analysis culminates in strategic recommendations intended to mitigate identified weaknesses, capitalize on strengths, and transform neutral aspects into opportunities for the widespread implementation of liquid hydrogen, thereby contributing to the broader objective of carbon-neutral aviation.

Keywords: Transport, Aviation, Liquid Hydrogen, Motor Fuel, Sustainable Aviation Fuels, Energy efficiency, Electrical equipment.

1. Introduction.

Traditionally viewed as a modern and progressive transport sector, civil aviation invariably occupies a prominent position in the development of national transport infrastructure. The introduction of novel, comfortable, high-speed, and economical aircraft into airline fleets necessitates the presence and ongoing development of aviation ground equipment to ensure prompt and high-quality technical and commercial maintenance of airfields.

An initial analysis of the diverse applications of aviation ground equipment, influenced by factors such as passenger and cargo traffic volume at a given airport, airfield dimensions and configuration, underscores the requirement for

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a substantial inventory of AGE, with quantities ranging from the hundreds to thousands of units.

2. Methods and materials

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:

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

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; $\mathbf{K_{serv}}$ – service factor:

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

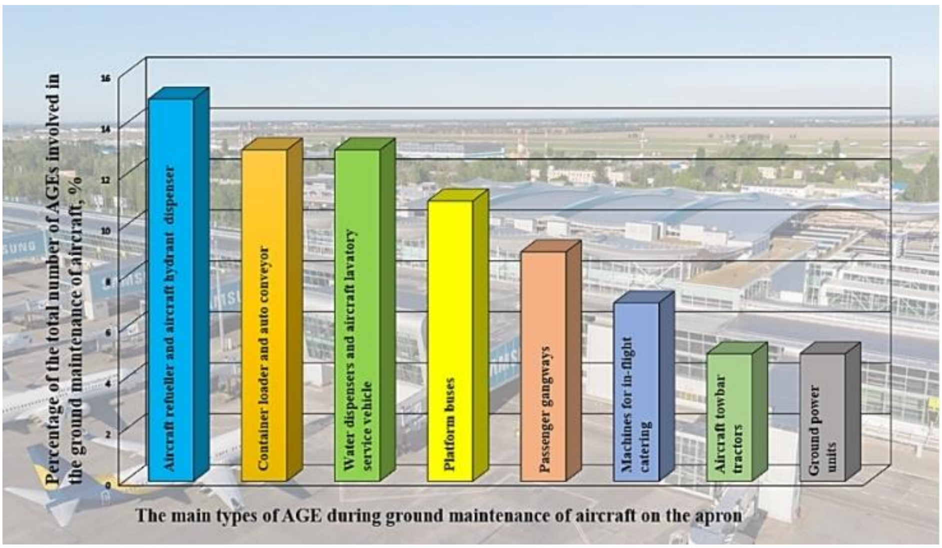
where C_{act} – is the actual number of aircraft take-offs per day; T_c – is the cycle time of maintenance of the aircraft by a special vehicle of a certain functional purpose; m – the number of special vehicles of a certain type that are simultaneously used for ground maintenance of aircraft; T_{daily} – 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 viability of hydrogen in transforming airport ground operation

The determination of the requisite quantity of AGE for aircraft ground handling can also be achieved through graphical means, employing appropriate nomograms. Statistical evidence indicates that a substantial proportion, approximately 85–90%, of airport special vehicles utilize internal combustion engines (operating on gasoline or diesel fuel) to power both their base chassis and specialized equipment, a factor that invariably influences the level of environmental safety within airport precincts and adjacent areas [2]. While the contribution of aircraft engine noise and harmful emissions to environmental pollution at airports is undeniable, the environmental risks arising from the operation of a significant number of AGE units [3] also constitute an important consideration.

Through an analysis of flight operation manuals for common civil aviation aircraft and technological schedules for aircraft ground maintenance, informed by statistical methods and expert evaluations, the segment of AGE types exhibiting the highest numerical presence on airport passenger and cargo platforms during ground-level aircraft maintenance was identified. A comprehensive quantitative and qualitative analysis of aviation ground equipment utilized for the operational maintenance of airfields necessitates distinct research and falls outside the scope of this chapter, notwithstanding the recognized significance of environmental risks associated with airfield machinery. Figure 1 presents a histogram illustrating the quantitative distribution of the most prevalent aviation ground equipment types on the platform, expressed as a percentage of the total special vehicles involved in aircraft operational maintenance processes.

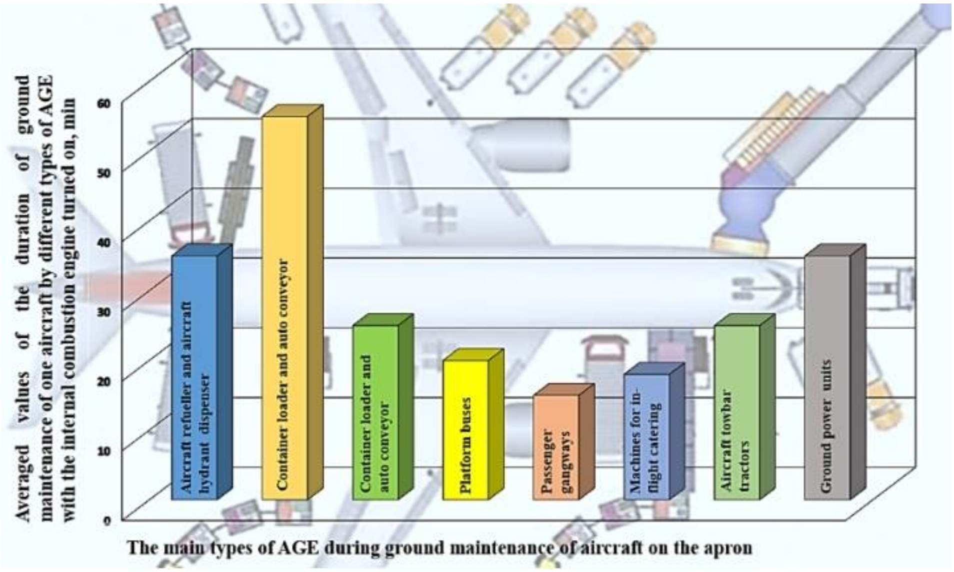


Rys. 1. Rozkład głównych typów AGE według ich ilości w naziemnej obsłudze technicznej statków powietrznych

Fig. 1. Distribution of the main types of AGE according to their quantity at ground levelaircraft maintenance

In addition to these quantitative indicators, determining the aggregate duration of their presence on the platforms is crucial, encompassing transit to and from the aircraft maintenance buffer zone, positioning, operational deployment, transition to transport mode, and return to the operational parking area (fig. 2).

The preceding analysis concerning the quantitative evaluation of diverse aviation ground equipment types and their operational duration with internal combustion engines (gasoline or diesel) during aircraft ground maintenance is, in our estimation, a decisive factor in establishing priority directions for the modernization of AGE power plants with the objective of enhancing the environmental conditions on airport aprons. The primary imperative involves the production (or modernization) of AGE types that are most numerically represented on the platform to incorporate electric motors as the principal energy sources for both the propulsion of these specialized vehicles and their intended operational functions.



Rys. 2. Rozkład głównych typów AGE według średniego czasu ich użytkowania z włączonymi silnikami spalinowymi podczas obsługi naziemnej jednego samolotu

Fig. 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

The integration of hydrogen engines presents a promising direction for the ecological modernization of AGE design. These engines employ a fundamentally distinct process for generating electric current within chemical reactors, contrasting with traditional electric motor operation. Significantly, hydrogen also demonstrates high performance characteristics as a combustible gas (tables 1, 2). Furthermore, ongoing advancements are being made in the technological domains of liquid and gaseous hydrogen production and storage.

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).

The utilization of liquid hydrogen as a propellant in aviation (table 4) yields water vapor as its primary combustion byproduct, thereby eliminating carbonaceous emissions during flight operations. This characteristic stands in marked contrast to conventional aviation fuels, which release substantial quantities of CO2 and other atmospheric pollutants. The transition to liquid hydrogen offers a significant pathway for reducing the aviation sector's contribution to air pollution and anthropogenic climate change. Possessing a high gravimetric energy density, liquid hydrogen presents an efficient fuel option for aviation applications.

Tabela 1. Charakterystyka termofizyczna wodoru

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.

Tabela 2. Porównanie właściwości tradycyjnej nafty lotniczej i ciekłego wodoru

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

Moreover, hydrogen can be generated from diverse sources, notably water electrolysis powered by renewable energy resources such as solar and wind. This production pathway allows for the generation of liquid hydrogen without concomitant CO2 emissions, aligning with global imperatives for a transition towards a more sustainable and circular energy paradigm. Investment in liquid hydrogen as an aviation fuel catalyzes technological innovation and the development of necessary infrastructure (fig. 3), fostering new markets and opportunities for economic growth, particularly in regions endowed with substantial renewable energy resources.

Tabela 3. Charakterystyka objętościowo-masowa różnych systemów magazynowania wodoru w porównaniu z benzyną

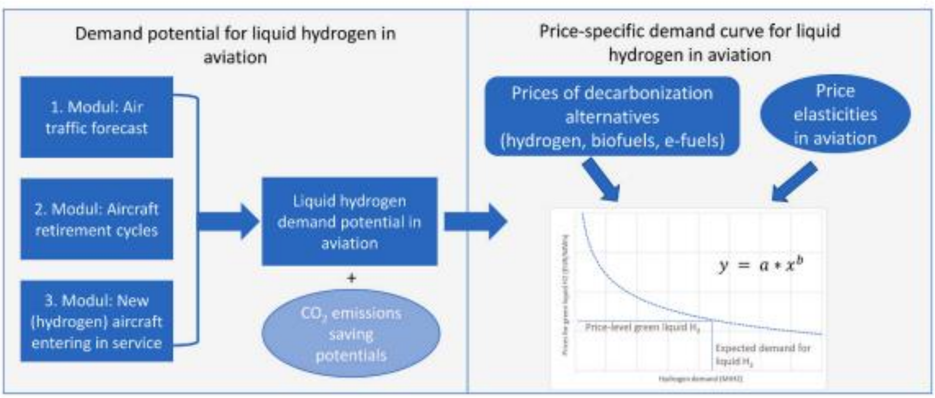
Table 3. Volume-Mass Characteristics of Various Hydrogen Storage Systems Compared to Gasoline

Indicator	**Gasoline**	**Compressed Hydrogen**	**Liquid Hydrogen**	**MgH2 Hydride**
Fuel mass, kg	53.5	13.4	13.4	18.1
Fuel volume, m^3	0.07	1.08	0.19	0.23
Tank mass, kg	13.06	136.1	181	45.4
Tank volume, m^3	0.08	1.83	0.28	0.25
Total system mass, kg	67	137.4	195	227

The establishment of a hydrogen economy has the potential to generate employment, stimulate technological progress, and mitigate dependence on finite oil and gas reserves. The utility of liquid hydrogen extends beyond the aviation sector; it serves as a versatile energy vector capable of integration into broader energy infrastructures for storage, transportation, and decarbonization initiatives across diverse industries. This inherent compatibility underscores its potential as a cornerstone of future sustainable energy ecosystems.

Notwithstanding its promise, the transition to liquid hydrogen within the aviation domain encounters significant challenges, including the imperative for substantial infrastructure investments, the need for technological advancements in storage solutions and fuel cell efficiency, and the establishment of robust safety protocols for handling and transportation.

Addressing these multifaceted challenges necessitates a concerted and coordinated effort among governmental bodies, industry stakeholders, and the research community [4].



Rys. 3. Charakterystyka popytu na ciekły wodór w lotnictwie

Fig. 3. Demand characteristics for liquid hydrogen in aviation

Tabela 4. Właściwości wodoru i niektórych porównywalnych substancji

Table 4. Properties of Hydrogen and Some Comparable Substances

	Valid at		**Hydrogen1**	**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/m³	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/m³	1.338	1.818	2.419	3.29
Density of gas	1.013 bara 0°C	kg/m³	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	cm²/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

In summation, the transition towards sustainable aviation fuels (SAF), with a particular emphasis on liquid hydrogen, represents a critical trajectory for the decarbonization of the aviation sector and the attainment of broader environmental and sustainability imperatives. Notwithstanding existing obstacles, the multifaceted benefits of liquid hydrogen—ranging from its favorable environmental attributes to its capacity to stimulate economic and technological innovation–underscore its potential as a transformative solution for achieving sustainable aviation.

The present essay aims to conduct a comprehensive evaluation of the viability of liquid hydrogen as a motor fuel within the aviation sector, utilizing the complementary analytical frameworks of PEST-analysis and SNW-analysis. The PEST-analysis will examine the macro-environmental factors –Political, Economic, Social, and Technological—that bear upon the adoption and implementation of liquid hydrogen in this industry. Conversely, the SNW-analysis will provide an internal assessment, focusing on the inherent Strengths, Neutrals, and Weaknesses of liquid hydrogen as a fuel alternative. This integrated analytical approach seeks to elucidate both the external opportunities and constraints, as well as the intrinsic advantages and challenges, associated with the transition to liquid hydrogen as a sustainable aviation fuel.

PEST analysis for liquid hydrogen adoption in aviation

PEST analysis (table 5) provides the external context. It examines the broader Political, Economic, Social, and Technological forces that will influence whether and how liquid hydrogen can be adopted within the aviation industry.

Tabela 5. Analiza PEST potencjalnej roli ciekłego wodoru w rozwoju zrównoważonego lotnictwa

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 Organi-zation**	**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
Econo-mic [6]	Cost implications, investment requirements	Market volatility, technolo-gical advance-ments	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

Tabela 5. Analiza PEST potencjalnej roli ciekłego wodoru w rozwoju zrównoważonego lotnictwa

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

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 Organi-zation	Action Program
Social [7]	High energy density, zero carbon emissions at point of use, potential for renewable sourcing	Public perception, environment-tal advocacy	Increasing as public awareness and environmental concerns grow	Essential for social acceptance and regulatory approval	Influences company image and market position	Educate the publicof environ-mental benefits
Techno-logical [8][9]	Advanced cryogenic storage tanks and fuel cell engines in development stages	Potential delays in technology commerciali-zation	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 capabili-ties and market readiness	Invest in R&D, prepare for integration of new technolo-gies

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.

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

SWN analysis for liquid hydrogen adoption in aviation

SNW analysis (table 6) provides the internal perspective. It focuses on the inherent Strengths, Neutrals, and Weaknesses of liquid hydrogen itself as a fuel for aircraft. This includes its environmental benefits, energy density, storage challenges, and current technological maturity.

Tabela 6. Analiza SWN potencjalnej roli ciekłego wodoru w rozwoju zrównoważonego lotnictwa

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. Summary

In summary, the application of PEST and SNW-analyses to the prospect of liquid hydrogen as an aviation motor fuel provides a comprehensive evaluation of its opportunities and impediments. The evolving political landscape, the dual nature of economic considerations, the influential role of societal factors, and the trajectory of technological progress collectively shape its potential. Realizing the promise of liquid hydrogen for sustainable aviation necessitates targeted investments, supportive policy frameworks, and sustained technological innovation to mitigate identified weaknesses and strategically leverage neutral attributes. This holistic analysis offers valuable insights for stakeholders seeking to advance the adoption of liquid hydrogen and ensure a sustainable future for the aviation industry.

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STRATEGICZNE I PERSPEKTYWICZNE BADANIA NAD WYKORZYSTANIEM CIEKŁEGO WODORU JAKO NISKOEMISYJNEGO PALIWA W LOTNICTWIE

Streszczenie

Przyjęcie ciekłego wodoru jako zrównoważonego paliwa lotniczego jest krytycznie analizowane w tym rozdziale poprzez kompleksową analizę PEST (polityczną, ekonomiczną, społeczną, technologiczną) i SNW (mocne i słabe strony). Uznając pilną potrzebę wynikającą z rosnących obaw o środowisko i znacznego śladu węglowego sektora lotnictwa, badanie bada zewnętrzne czynniki sprzyjające i utrudniające (PEST) wraz z wewnętrznymi zaletami i ograniczeniami (SNW) wykorzystania ciekłego wodoru. Analiza kończy się zaleceniami strategicznymi mającymi na celu złagodzenie zidentyfikowanych słabości, wykorzystanie mocnych stron i przekształcenie neutralnych aspektów w szanse na powszechne wdrożenie ciekłego wodoru, przyczyniając się tym samym do szerszego celu, jakim jest lotnictwo neutralne pod względem emisji dwutlenku węgla.

Słowa kluczowe: Transport, Lotnictwo, Ciekły wodór, Paliwa silnikowe, Zrównoważone paliwa lotnicze, Efektywność energetyczna, Sprzęt elektryczny

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GEOPOLITICAL RISKS AND SECURITY OF GREEN HYDROGEN SUPPLY

The chapter analyses geopolitical risks and challenges related to the development of green hydrogen in Europe. Green hydrogen, produced from renewable energy sources, is a central element of the EU's decarbonization strategy and a response to energy security concerns following Russia's invasion of Ukraine in 2022. The EU aims to produce and import 10 million tons of renewable hydrogen annually by 2030. However, scaling up this market introduces new international dependencies on raw materials (e.g., rare metals like iridium and platinum) and infrastructure (e.g., pipelines, LNG terminals). A major concern is avoiding overdependence on a single import route, which the EU addresses by building diversified "hydrogen corridors" (e.g., H2Med, Baltic Hydrogen Corridor) and forming global partnerships (Africa, the Middle East, South America). The document reviews national strategies of Germany, Spain, the Netherlands, and Norway, which vary but share a focus on supply security. Despite the potential, Europe faces global competition (e.g., from the U.S. and China), resource scarcity, and high investment costs. The findings emphasize the need for a flexible, integrated approach that combines energy, foreign, and industrial policy to develop a secure green hydrogen supply chain. Only such a comprehensive strategy will ensure that green hydrogen becomes a cornerstone of European energy security, rather than a new vulnerability.

Keywords: energy security, geopolitics, supply diversification, energy transition

1. Introduction

Green hydrogen that is, hydrogen produced using renewable energy sources (e.g., by wind- or solar-powered water electrolysis) is seen as a key energy carrier in the transition to climate neutrality. In the European Union's energy strategies, hydrogen plays an important role in decarbonizing hard to-electrify sectors such as steel, chemicals, heavy transport and aviation. At the same time, following Russia's invasion of Ukraine in 2022 and the resulting energy crisis, hydrogen has gained an additional dimension as an element of Europe's energy security. The EU's plan to become independent of Russian fuels REPowerEU, envisions accelerating the development of the hydrogen economy, setting ambitious goals: by 2030.

The Union wants to achieve the capacity to produce 10 million tons of renewable hydrogen per year and import an additional 10 million tons through imports. Hydrogen is thus expected to help replace fossil fuels in Europe's energy

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mix and strengthen the resilience of the energy system to geopolitical shocks. However, the development of green hydrogen on a mass scale poses a number of geopolitical challenges. These include the security of supply chains both of hydrogen itself and its carriers, as well as of the raw materials and technologies needed to produce it, the new international dependencies that will be created with global hydrogen trade. As Europe strives to become a hydrogen leader, it must factor these risks into its strategies. Past experience (heavy reliance on oil imports from OPEC or natural gas from Russia) shows that the issue of supply diversification and partner stability is crucial to energy security. This paper focuses on the geopolitical aspects of green hydrogen development in Europe. It analyzes the risks and opportunities facing European countries, discusses the strategies of selected countries of Germany, Spain, the Netherlands and Norway, and initiatives to secure hydrogen supplies in the context of current international challenges (dependence on critical raw materials, armed conflicts, energy crises).

2. Geopolitical determinants of green hydrogen supply

Hydrogen as an energy carrier could fundamentally change global energy geopolitics, reducing the importance of traditional fossil fuels and relationships based on their export. On the one hand, green hydrogen production is theoretically possible in many regions of the world, especially where there is an abundance of cheap renewable energy (solar, wind). Countries with abundant renewable energy potential for example, in the Middle East, North Africa, Australia or South America, could become hydrogen exporters, with geo-economic and geopolitical implications. On the other hand, the new global hydrogen market will create a network of relationships and dependencies between producers and importers, potentially creating new risks. For Europe, the key challenge is to avoid green hydrogen becoming another critical imported fuel, vulnerable to political pressure or supply disruptions.

Current geopolitical dynamics are having a strong impact on Europe's hydrogen strategies. The 2022 war in Ukraine made EU countries aware of the dangers of depending on energy supplies from unstable or hostile suppliers. In response, European countries have significantly raised their targets and accelerated their hydrogen efforts. In Northwest Europe, for example, a region accounting for about half of Europe's hydrogen demand, several countries have doubled their national hydrogen production targets after 2022. In total, countries in the region are now planning to build 30-40 GW of electrolyzer capacity by 2030 (Norway, as an exporter, has adopted a technology-neutral approach, also allowing so-called "blue" hydrogen from CO_2-capture gas).

These measures have the dual purpose of accelerating decarbonization on the one hand, and strengthening energy security by reducing fossil fuel imports on the other. This is because low-carbon hydrogen can, in the medium term, reduce dependence on natural gas or oil imports, becoming a locally produced substitute, for example, in the chemical industry or transportation.

It is worth noting, however, that paradoxically the implementation of ambitious hydrogen plans itself faces risks associated with global supply chains and raw material markets. The production of electrolyzers, or hydrogen production equipment, depends on a number of critical raw materials. For example, popular PEM electrolyzers use Platinum group metals, particularly iridium and platinum, which are rare raw materials and mined in a handful of countries such as South Africa and also Russia. With a global surge in demand for these metals, there is a risk of supply bottlenecks and cost increases, which could delay the scaling of hydrogen technologies. Green hydrogen is therefore vulnerable to mineral price shocks, just as the fossil fuel economy has been vulnerable to oil price fluctuations.

The European Union recognizes this problem because the EU's critical raw materials strategy and efforts to develop its own production of electrolyzers (e.g., IPCEI hydrogen projects) aim to reduce this dependence by developing local value chains and recycling metals. Nevertheless, in the coming years, Europe will remain partially reliant on imports of components and materials for hydrogen technologies, with suppliers such as China dominating (e.g., in the area of solar panel production, alkaline electrolyzers, etc.).

3. New trade routes and import dependencies

Since projections for hydrogen demand in Europe far exceed domestic production capacity, the question of large-scale imports arises. Germany estimates that it will be able to meet only 30-50% of its hydrogen demand (estimated at 95-130 TWh in 2030) from domestic sources by 2030, and only 30% of demand by 2045. This means permanent dependence of the EU's largest economy on imported hydrogen. According to the government's strategy, Germany will remain one of the world's largest importers. Accordingly, it was stated unequivocally that "ensuring a stable, secure and diversified supply of hydrogen and its derivatives to the economy is in Germany's strategic interest." These words capture the essence of the challenge for all of Europe: diversifying supply sources and minimizing the risk of supply disruptions are a strategic priority. EU countries are striving to avoid over-concentration of hydrogen imports from one direction or country, lest they repeat the mistake of over-dependence, as happened with gas imports from Russia before 2022. European strategies therefore assume the development of multiple "hydrogen corridors" - routes for importing green hydrogen from different regions. The most economically viable way to transport large quantities of hydrogen is through pipelines, especially over distances of up to several thousand kilometers. Therefore, Germany and other countries plan to import hydrogen primarily through pipelines from European countries and their close neighbors. Germany's strategy identifies countries in the North Sea region

(Denmark, the Netherlands, Belgium, Norway, as well as the UK through submarine connections) and the Baltic Sea Basin (including the Baltic Hydrogen Collector project connecting the Baltic and Nordic countries) as prospective sources of pipeline supply. Another direction is the Southwest Corridor from the Iberian Peninsula - Spain and Portugal through France to Central Europe. In parallel, a southern corridor is planned from North Africa (e.g., Algeria, Tunisia) through Italy and Austria to Germany. These geographically diverse routes are intended to ensure that hydrogen flows into Europe from different directions, increasing resilience to possible local political or economic crises. It's worth noting that European discussions currently do not assume hydrogen imports from Russian or Ukrainian territory-war and political risks exclude these countries as reliable suppliers for the future, even though they could technically potentially produce large quantities of hydrogen (Russia from natural gas, Ukraine from surplus nuclear or RES). In addition to transportation via pipelines, supplies of hydrogen in the form of derivatives such as ammonia, methanol or synthetic fuels are also being considered. These are easier to transport by ship or rail, as they use the existing infrastructure for transporting liquid products and chemicals. However, the disadvantage of such a solution is the energy loss in converting hydrogen into a carrier and recovering it again at the recipient. Therefore, strategies such as Germany's prefer to use imported derivatives directly in industry (e.g., ammonia in fertilizers, methanol as a chemical feedstock) to avoid additional losses. Germany anticipates that LNG terminals currently under construction will also serve to import ammonia or liquid hydrogen in the future. According to legal requirements, such terminals are to be adapted to handle hydrogen or its carriers by 2044 at the latest.

4. Examples of countries' strategies and hydrogen projects in Europe

Europe as a whole has clearly defined hydrogen goals, but individual countries are pursuing them in different ways based on their circumstances and interests. It is worth examining the approach of selected leaders in this field. Europe as a whole has clearly defined hydrogen goals, but individual countries are pursuing them in different ways based on their circumstances and interests. It is worth examining the approach of selected leaders in this field.

Germany, as the EU's largest economy, sees hydrogen as the foundation of the country's industrial transformation and energy security. Already in 2020. Germany adopted a national hydrogen strategy, and in 2023 updated it and developed a strategy for importing hydrogen and derivatives. As mentioned, Germany assumes the need to import about 70% of the hydrogen needed. To this end, the German government is actively developing hydrogen diplomacy. It has entered into formal hydrogen partnerships with 15 countries outside the EU (including Norway, Chile, Namibia, South Africa, Morocco, Algeria, Saudi

Arabia, the UAE, Australia), which provide a policy framework for future trade contracts and investments. Positions of "hydrogen attachés" (H2-Diplo) have been created at many German diplomatic missions to facilitate cooperation between companies and research institutes and partners abroad. Berlin has also launched the H2Global financial instrument, which, through a double auction mechanism, is supposed to subsidize the price difference between costly green hydrogen imports and the price domestic consumers are willing to pay is supposed to allow profitable hydrogen trade to take off before market forces kick in. In terms of infrastructure, Germany plans to build a national hydrogen pipeline network and connections to its neighbors. One example is the H2Med project, a hydrogen supply corridor from the Iberian Peninsula announced in late 2022. It includes, among other things, an offshore pipeline from Spain to France (known as BarMar) and a Portugal-Spain connection. H2Med is expected to enable the transmission of up to 2 million tons of H_2 per year, and is scheduled to become operational in 2030. In 2023, German operator OGE joined the project to extend the trunk line all the way to Germany, underscoring the importance of this route to the security of hydrogen supply to the German economy. In parallel, Germany was studying the possibility of importing hydrogen from Norway via an undersea pipeline. There were plans to build infrastructure to produce so-called blue hydrogen from natural gas in Norway and transport it by pipeline to Germany, but in 2024 Equinor announced the suspension of this project due to excessive costs and insufficient demand guarantees. This shows that despite the political interest, hydrogen projects must also be business feasible. The lack of long-term offtake contracts and the high capital intensity of the infrastructure are major barriers to investment.

With excellent natural conditions for producing low-cost solar and wind power, Spain sees green hydrogen development as an opportunity for industrial reinvestment and export of renewable energy in a new form. The Spanish government had already adopted a Hydrogen Strategy in 2020 to build 4 GW of electrolyzer capacity by 2030 (which was 10% of the EU target at the time). After the outbreak of war in Ukraine and the announcement of the REPowerEU plan, this ambition was significantly increased. According to the latest declarations, Spain aims to install up to 11 GW of electrolyzers by 2030. Surplus green hydrogen production would be exported. The construction of infrastructure to allow the transmission of energy from the Iberian Peninsula to the rest of Europe, which has historically been a weak point (limited interconnectors across the Pyrenees), has become a priority. The H2Med initiative, described above, is crucial from Spain's point of view, that it will enable the physical export of hydrogen to France and on to Germany. In addition, Spain is developing its internal hydrogen network: operator Enagás is proposing to create two transmission axes north and east, connecting the country's main hydrogen production and consumption regions. Spanish energy companies are investing in a number of "hydrogen valleys" projects, or clusters of H_2 production and use, often located around port and industrial hubs (e.g., at the port of Valencia, in Andalusia, in the north in Baskonia). Also worth mentioning is Madrid's growing hydrogen diplomacy, Spain sees hydrogen as part of strengthening Euro-Mediterranean cooperation. Spanish companies are forging partnerships in Latin America, e.g. Chile, Africa and in Morocco, to jointly develop hydrogen projects, which could make Spain an intermediary between these regions and the EU market.

The Netherlands plans to become a global import and transit hub for hydrogen in Northern Europe and has a long tradition as an energy trading center (gas, oil ports) and intends to maintain this role in the hydrogen era. The Dutch government has adopted a hydrogen strategy involving both the development of its own production (using energy from offshore wind farms to power electrolyzers on land and potentially at sea) and the creation of an import hub at the port of Rotterdam. The Port of Rotterdam is already collaborating globally on H_2 supply chains - more than 150 projects to import green hydrogen or its carriers from various countries around the world are being studied. Dutch companies and institutes (e.g., TNO) have entered into cooperation agreements with Namibia, South Africa and Morocco, among others countries with high potential for green hydrogen exports to prepare the ground for future trade and identify logistical challenges. In 2023. The Netherlands and Spain signed a hydrogen cooperation agreement to facilitate links between the Iberian Peninsula and Dutch ports. Four major NL ports (Rotterdam, Amsterdam, Eemshaven, Vlissingen) have developed plans to build terminals for importing hydrogen - in liquid form, ammonia, methanol or LOHC. Adaptation of existing gas infrastructure is also underway: operator Gasunie is coordinating the European Hydrogen Backbone initiative, which involves converting some gas pipelines into a hydrogen network linking Europe. The Netherlands, lying centrally, will be a key part of this system, linking supplies from seaports to customers at home and in neighboring Germany. Projections indicate that a significant portion of the Netherlands' hydrogen imports could go further to Germany, which will be its largest market. In addition to imports, the Netherlands is also investing in hydrogen storage - there are plans to use salt caverns for seasonal H_2 storage as an energy buffer. In this way, the hydrogen is expected to serve not only the current needs of the industry, but also strengthen security of supply by creating reserves in case of import interruptions or production shortfalls from RES.

In contrast, Norway, as a major exporter of energy i.e. oil and gas from outside the EU, is seen as a natural partner for Europe in the hydrogen era. Norway's hydrogen strategy takes a technology-neutral approach, supporting both green hydrogen from surplus low-cost hydro and wind power, and low-carbon hydrogen produced from natural gas using CO_2 capture and storage (so-called blue hydrogen). Norway has unique strengths: an almost 100% emission-free electricity mix (hydropower), large gas resources, and CO_2 storage infrastructure under the bottom of the North Sea (projects such as Northern Lights).

The Norwegian government is betting that hydrogen can become another export commodity to support the energy transition of both Norway and its foreign customers. For the past few years, the Norwegians have been working intensively with Germany on the concept of a direct hydrogen link but as mentioned above, the pipeline project has been suspended for economic reasons. This has prompted Norway to look for other avenues - perhaps exporting hydrogen in the form of ammonia by sea, or developing smaller cross-border projects (such as supplying hydrogen to Denmark or Sweden for shipping). In parallel, Norway is using hydrogen to decarbonize its own economy: examples include the introduction of liquid hydrogen-powered passenger ferries into the Norwegian fjords (MF Hydra project launched in 2021) or plans to use hydrogen in the metallurgical and chemical industries. Norway's political stability and close relations with the EU, such as the European Economic Area, make it a relatively secure supplier. Potential long-term hydrogen contracts from Norway would be less fraught with geopolitical risk than imports from some other regions. From Norway's perspective, however, price competitiveness remains a challenge. The European hydrogen market is only just taking shape and requires regulatory and financial support for potential producers (like Equinor) to have certainty of sale. The lack of such certainty has put the brakes on plans for large-scale exports. Norway is therefore focusing on the gradual development of the technology and a possible role as a supplier, but full realization of its hydrogen potential will have to wait until a receptive and mature market is established in Europe.

5. Opportunities and risks against a global backdrop

The development of the green hydrogen market presents Europe with both opportunities and threats. Opportunities include the possibility of reducing dependence on fossil raw materials and the revival of domestic industry in new sectors (production of electrolyzers, new materials, infrastructure). European industry faces an opportunity to capture some of the added value from the global hydrogen economy, for example, by becoming a supplier of technology or high-quality hydrogen products. Hydrogen trade can become a tool for strengthening relations with countries aspiring to become clean energy exporters. The EU is already developing energy partnerships with countries such as Namibia, Australia and Chile, offering investment assistance in exchange for future supplies of green hydrogen or its carriers. This is part of a broader Global Gateway strategy to build sustainable infrastructure and economic links, while promoting a global energy transition zero-carbon. With hydrogen, countries in North Africa or the Middle East can diversify their economies (hitherto based on oil and gas) and enter new supply chains - which in the long run could promote their economic and political stability. For Europe, this would mean a more diverse set of energy partners, none of which would be as dominant as Russia has been in the gas market in recent decades. However, the risks cannot be ignored. The risk of concentration of supply of certain strategic raw materials (e.g., metals for electrolyzers) has already been mentioned. In addition, some experts point to uncertainty about the real scale of available hydrogen imports by 2030. There are studies suggesting that global green hydrogen production capacity may develop more slowly than the EU assumes, and that European demand will largely be met by domestic production. For example, a report by the NGO Transport & Environment argued that the EU's hydrogen demand in 2030 (about 4-5 Mt) can be covered by its own production, making imports unnecessary.

The industry association Hydrogen Europe, on the other hand, argues against such an approach, pointing out that the European project pipeline already indicates a demand of 8-10 Mt, and that imports will be needed to meet climate and energy security targets. This debate shows that there is uncertainty about future supply and demand hydrogen infrastructure planning is fraught with the risk of erroneous assumptions. If Europe overestimates demand and invests in expensive terminals or pipelines that go unused, it will incur economic costs. If, in turn, demand or supply is underestimated, a gap and shortage of hydrogen could emerge, threatening continuity of supply for the industry. Flexibility and graded investment seem a sensible approach in the face of these uncertainties. Another major geopolitical risk is global competition for technology and investment. A race between major economic powers for dominance in the clean technology industry, including hydrogen, has been evident in recent years. An example is the US Inflation Reduction Act (IRA) of 2022, which provides generous tax breaks for, among other things, green hydrogen production in the US. This policy attracts investment and may cause some of the capital and projects originally planned in Europe to move across the Atlantic for the benefit of better conditions. This poses a challenge for the EU; to keep the hydrogen industry growing at home, it needs to create competitive conditions through, for example, the Hydrogen Fund, contracts for difference or other support mechanisms. If Europe does not keep pace, there is a risk of technological dependence on external equipment suppliers or even importing hydrogen from regions that are quicker to develop production on the scale of the Middle East, the US and Australia.

In an extreme scenario, the future "OPEC of hydrogen" could emerge from among the exporting countries (although for now the sector is too fragmented to talk about a cartel). In order to secure supply, Europe will have to seek stable relationships with leading producers and actively participate in establishing international standards and regulations for hydrogen trade so that the market is transparent and conducive to long-term stability.

6. Methodology

This paper is based on a multi-faceted analysis of scientific literature, industry reports and policy documents related to the topics of green hydrogen, energy security and current geopolitical conditions in Europe. The method used was critical review (desk research), which involves systematically collecting and organizing the data found in secondary sources, while verifying their reliability and validity. The starting point was to define key concepts and issues, such as "hydrogen geopolitics," "security of supply" and "commodity risk," as well as to identify the main factors shaping the development of the European hydrogen market (including the technological context, environmental requirements and member state strategies).

In a further step, a selective case study was made, including hydrogen strategies and specific projects implemented in Germany, Spain, the Netherlands and Norway. The choice of these countries was dictated by their important role in the European energy transition and their different economic and geopolitical conditions, which enabled a comparative analysis of potential risks and opportunities. Using available government reports, publications of international organizations (IRENA, IEA, among others) and data from news agencies (Reuters), the actual pace of development of hydrogen technologies, planned import and export paths and opportunities for supply diversification, which is crucial for energy security, were assessed.

The analysis also used an interdisciplinary perspective, combining the methodologies of international relations sciences and geopolitics with knowledge of energy and climate policy. This allowed for an integrated look at the issues of hydrogen transportation infrastructure, necessary critical raw materials and potential support mechanisms such as contracts for difference or international hydrogen partnerships. In critically evaluating the sources, particular attention was paid to the consistency of the information and the degree to which it was corroborated by various research and government institutions. This made it possible to identify discrepancies in forecasts of future supply volumes, investment costs or the timing of major infrastructure projects.

At the final stage, the results of the analysis were synthesized and confronted with the results of similar scientific studies and the available scenarios of international agencies. This resulted in a multifaceted picture of the geopolitical risks associated with green hydrogen supply chains in Europe, as well as a comprehensive overview of existing and planned instruments to minimize these risks. The paper highlights both the barriers to the rapid expansion of the European hydrogen market (including the limited availability of raw materials for electrolyzer production and differences in national interests) and the potential benefits of developing a new industry and strengthening the continent's energy security. The applied research approach has therefore identified key challenges and recommendations for the sustainable and efficient development of the hydrogen sector in the context of European energy security and stability policy.

7. Summary

Europe stands at the threshold of a new energy era in which green hydrogen could play a role comparable to that played by oil or natural gas in the 20th century. This transition holds the promise of significant emissions reductions and independence from fossil fuels, but at the same time requires facing the geopolitical challenges that will shape the security of energy supply in the coming decades.

An analysis of the geopolitical risks associated with hydrogen supply chains reveals a complex picture: on the one hand, greater distribution of potential hydrogen producers around the world can prevent the concentration of supplies in the hands of a few countries, as has happened with oil and gas. On the other hand, new dependencies are emerging on access to critical raw materials, technology or transportation infrastructure which could become subject to competition and international tensions. Europe is already taking steps to minimize these risks: diversifying future import destinations through initiatives such as the H2Med corridors, the Baltic Hydrogen Corridor or agreements with African countries; investing in the development of indigenous hydrogen production capacity (40 GW of electrolyzers by 2030) and supporting domestic industry in building key elements of the value chain; creating financial mechanisms to stimulate the market (European Hydrogen Bank, contracts for difference) and developing strategic reserves (hydrogen storage in caverns).

Thanks to lessons learned from previous energy crises, the issue of security of supply is integrally woven into European hydrogen development plans. However, it is important to remain realistic as a recent report by the European Court of Auditors showed, the EU's current hydrogen targets (20 million tons by 2030) are extremely ambitious and may prove difficult to achieve in the timeframe envisioned. This requires accelerating investment and removing barriers, including geopolitical ones. The continuation of the war in Ukraine, instability in the Sahel region or rival powers could affect the pace and cost of hydrogen projects. Therefore, the European strategy must be flexible and resilient to changes in the environment, combining the development of its own production capacity with the building of trusted import partnerships.

In conclusion, green hydrogen offers Europe an opportunity for an unprecedented transformation of its energy system toward sustainability and security, but the path to that goal requires taking geopolitical risks into account at every stage. Only a comprehensive approach that integrates energy and climate policy with foreign, industrial and raw materials policy will make it possible to build stable and resilient hydrogen supply chains. Europe seems aware of these challenges and is taking the first steps to ensure that the "new hydrogen era" benefits both the climate and the security and prosperity of its citizens. The next few years will show to what extent the ambitious plans will be turned into reality and whether green hydrogen will become a pillar of European energy security, instead of its potential weak link.

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RYZYKA GEOPOLITYCZNE I BEZPIECZEŃSTWO DOSTAW ZIELONEGO WODORU

Streszczenie

Dokument analizuje geopolityczne ryzyka i wyzwania związane z rozwojem zielonego wodoru w Europie. Zielony wodór, wytwarzany z odnawialnych źródeł energii, stanowi kluczowy element strategii Unii Europejskiej w zakresie dekarbonizacji i zwiększenia bezpieczeństwa energetycznego, zwłaszcza po inwazji Rosji na Ukrainę w 2022 roku. UE zakłada produkcję i import po 10 milionów ton zielonego wodoru rocznie do 2030 roku. Jednak rozwój tego rynku wiąże się z nowymi zależnościami międzynarodowymi – zarówno surowcowymi (np. rzadkie metale jak iryd czy platyna), jak i infrastrukturalnymi (np. gazociągi, terminale LNG). Kluczowym ryzykiem jest nadmierna koncentracja importu z jednego kierunku, co UE próbuje ograniczać poprzez rozwój tzw. „korytarzy wodorowych" (np. H2Med, Baltic Hydrogen Corridor) i zróżnicowane partnerstwa (Afryka, Bliski Wschód, Ameryka Płd.). Analizowane są strategie wybranych krajów: Niemiec, Hiszpanii, Holandii i Norwegii, które różnią się podejściem, ale łączy je dążenie do bezpieczeństwa dostaw. Mimo potencjału, Europa musi mierzyć się z rywalizacją globalną (np. z USA i Chinami), ograniczonymi zasobami i wysokimi kosztami inwestycji. Wnioski podkreślają konieczność elastycznej, zintegrowanej strategii, łączącej politykę energetyczną, zagraniczną I przemysłową, by zielony wodór stał się nie słabym ogniwem, lecz filarem bezpieczeństwa energetycznego Europy.

Słowa kluczowe: bezpieczeństwo energetyczne, geopolityka, dywersyfikacja dostaw, transformacja energetyczna

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MATHEMATICAL MODELLING DURING STUDIES OF THE STRENGTH OF STRUCTURAL ELEMENTS IN THE ATMOSPHERE OF HYDROGEN AND ITS MIXTURES

This chapter presents a comprehensive study on the mathematical modelling of the behaviour of structural materials under the influence of hydrogen and its mixtures. The motivation stems from the challenges of hydrogen embrittlement and strength degradation in metals, which are crucial issues for the development of reliable hydrogen energy infrastructure. The authors describe a modelling framework that includes hydrogen transport, microstructural degradation, and the establishment of relationships between mechanical strength and hydrogen concentration. Special attention is given to differentiating between diffusible and trapped hydrogen and the role of stress fields in the redistribution of hydrogen. Calculations were performed for various steel types to evaluate hydrogen concentration near crack tips and stress concentrators. The paper also covers modelling of hydrogen redistribution kinetics in bimetallic welds, showing the critical role of cooling rates in local supersaturation and delamination risk. Experimental validation is provided through metallographic analysis and numerical simulations. The proposed models allow for estimating critical hydrogen concentrations and assessing failure risks in complex material systems, contributing to the design of safer hydrogen storage and transportation components. The study confirms the effectiveness of mathematical modelling as a predictive tool to evaluate durability and prevent structural failures in hydrogen-exposed environments.

Keywords: hydrogen embrittlement, hydrogen diffusion, strength degradation, trapped hydrogen, bimetallic welds, fracture mechanics, mathematical modelling, structural materials

1. Introduction

The use of hydrogen in transportation, energy, and industry is highly promising due to its high energy density, zero CO_2 emissions during combustion, and the possibility of production from renewable energy sources.

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The hydrogen economy is expected to play a crucial role in the global energy balance in the coming decades [1,2].

However, despite its advantages, hydrogen presents significant challenges for modern structural materials. The issue of material degradation under the influence of hydrogen is one of the key obstacles to the widespread adoption of hydrogen technologies [3,4]. Hydrogen embrittlement, the formation of microcracks, and porosity in materials exposed to hydrogen significantly reduce their ductility and strength, potentially leading to premature structural failures. This is particularly critical for hydrogen storage, transportation, and utilization systems that operate under high pressure and challenging conditions.

To understand and address these problems, effective approaches to mathematical modeling of material degradation processes under hydrogen exposure are required. Such models enable the prediction of material behavior in a hydrogen environment, assessment of reliability, and estimation of service life. The application of mathematical models combined with experimental data allows not only the optimization of material selection for specific conditions but also the development of new structural materials resistant to hydrogen corrosion.

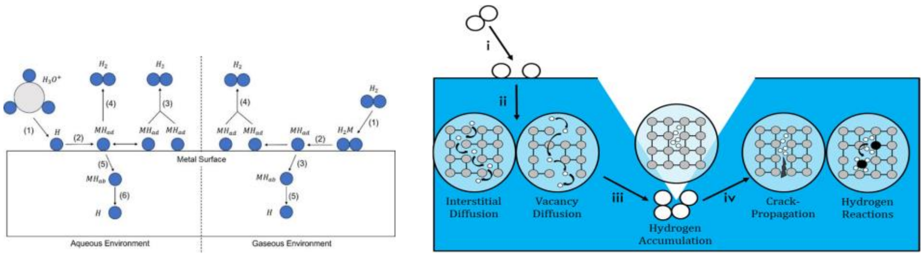
Thus, research on the impact of hydrogen on structural materials, the development of models for predicting their durability, and the creation of new materials are crucial for ensuring the safe and sustainable implementation of hydrogen energy.

Under constant load, a necessary condition for damage is the dissociation of molecular hydrogen into atomic hydrogen (Fig.1a) [4]. If atomic hydrogen penetrates the crystal lattice, the processes of physicochemical and electrochemical effects become similar: in both cases, atomic hydrogen diffuses into critical regions. These may include internal defects, where molecular hydrogen forms due to recombination at internal phase boundaries, leading to high pressure. This process may also involve diffusion into the region of triaxial stress in front of a crack tip or interactions with dislocations.

Hydrogen dissolves in almost all metals, altering their physicomechanical properties and causing hydrogen degradation, which is responsible for catastrophic failures in chemical, oil extraction, transportation, and other types of equipment.

Therefore, hydrogen degradation modeling should include the following stages (Fig.1b) [5]:

- Modeling the transport of hydrogen in metal
- Modeling the degradation of microstructural properties
- Establishing empirical and semi-empirical relationships between strength and hydrogen content.



a) b)

Rys. 1. Możliwe drogi transportu wodoru (a) [4] i schematyczna ilustracja oddziaływania atomów wodoru z siecią krystaliczną metalu (b) [5].

Fig.1. Possible ways of hydrogen transport (a) [4] and schematic illustration of hydrogen atoms interacting with metal crystal lattice (b) [5].

2. Models of metal-hydrogen interaction

Hydrogen degradation modeling should include the following stages:

- Modeling the transport of hydrogen in metal
- Modeling the degradation of microstructural properties
- Establishing empirical and semi-empirical relationships between strength and hydrogen content.

Depending on the position of hydrogen atoms in metals, it is classified into two types: hydrogen atoms in normal interstitial lattice sites (diffusible or lattice hydrogen) and trapped hydrogen. The concentration of diffusible hydrogen is related to the hydrogen concentration gradient C_L, hydrostatic stress gradients σ, and temperature T [6]:

$$\frac{\partial C_L}{\partial t} = div\left\{ D_L \left[\nabla C_L - \frac{C_L V_{\mathrm{H}}}{RT} \nabla \sigma + \frac{C Q_*}{RT^2} \nabla T \right] \right\}, \tag{1}$$

where D_L is the diffusion coefficient of hydrogen in the lattice sites, V_H is the molar volume of hydrogen, R is the gas constant, i.e. 8.314 J/(mol K), and T is the absolute temperature.

Considering the equilibrium relationship between diffusible and trapped hydrogen and Oriani's theory, the concentration C_T is related to C_L [6]:

$$C_T = \frac{N_T K_T C_L}{K_T C_L + N_L} \tag{2}$$

To evaluate the effect of plastic strain ε_{pl} on the number of trapping sites N_T, the following relationship was used [7]:

$$\log_{10} N_T = 23{,}26 - 2{,}33\exp(-5{,}5\varepsilon_p)\,. \qquad (3)$$

Taking this into account, the hydrogen diffusion equation is written as follows:

$$D^* \frac{\partial C_L}{\partial t} - \nabla\left(D_L \nabla C_L\right) + \nabla\left(\frac{D_L C_L V_\mathrm{H}}{RT}\nabla\sigma_h\right) + \theta_T \frac{\partial N_T}{\partial \varepsilon_p}\frac{\partial \varepsilon_p}{\partial t} = 0 \qquad (4)$$

where D^* is the effective diffusion coefficient depending on C_L, C_T and θ_T is defined as:

$$D^* = \frac{C_L + C_T\left(1-\theta_T\right)}{C_L} \qquad (5)$$

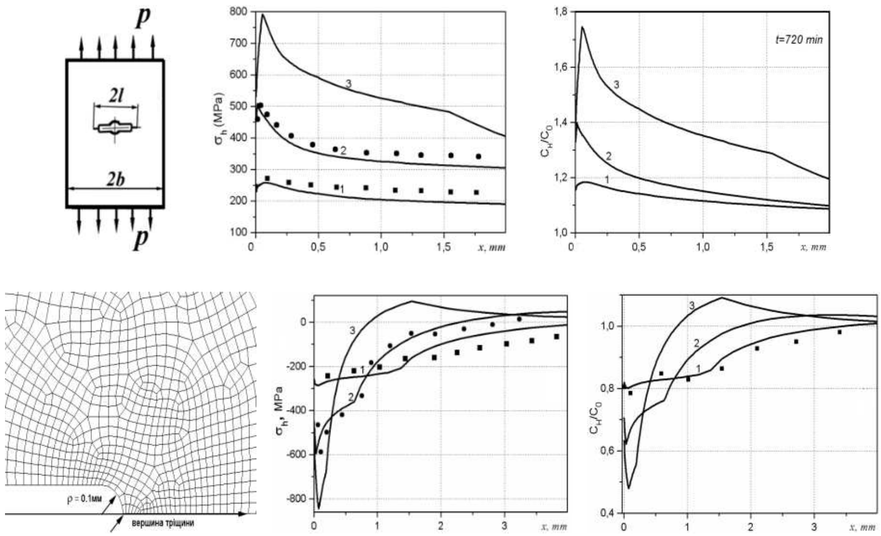
To solve the diffusion equation (4), it is necessary to determine the stress and strain fields near the defect. According to literature data [7], the influence of hydrogen on the yield strength is described as follows:

$$\sigma_{YS}\left(\varepsilon_p, c\right) = \left(\xi \cdot c + 1\right)\sigma_0 \cdot \left(1 + \frac{\varepsilon_p}{\varepsilon_0}\right)^m \qquad (6)$$

where σ_0 is the yield strength in the absence of hydrogen (e.g., in air), *c* is the total hydrogen concentration measured as atomic ratio, ε_0 is the strain corresponding to σ_0, and *m* is the work-hardening exponent. ξ is the coupling parameter that reflects the hydrogen influence on yield strength. Hydrogen-induced softening occurs when $\xi < 0$, while hydrogen-induced hardening is observed when $\xi < 0$.

3. Features of the distribution of hydrogen concentration near the stress concentrator depending

Using the described calculation algorithm, we theoretically determined and experimentally confirmed [8-13] the distribution of hydrostatic stress and hydrogen concentration along the crack extension in a uniformly stretched plate, as well as after complete unloading of specimens using true stress-strain diagrams of hydrogenated metal (Fig. 2) [8].



Rys. 2 Rozkład naprężeń hydrostatycznych i stężenia wodoru w strefie wstępnego pękania podczas obciążenia i po całkowitym rozładowaniu: 1 - stal 20; 2 - 65G; 3 - 40X (linie - obliczenia; punkty - eksperyment) [8]

Fig. 2. Hydrostatic stress and hydrogen concentration distribution in the prefracture zone during loading and after complete unloading: 1 – steel 20; 2 – 65G; 3 – 40X (lines – calculation; points – experiment) [8]

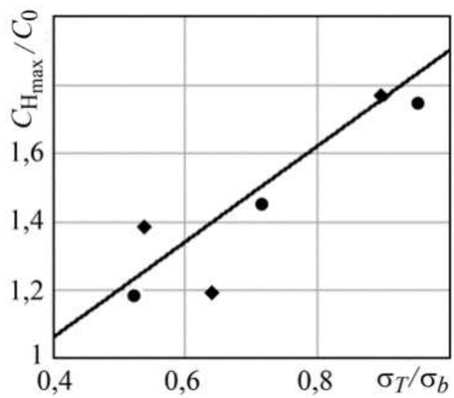
Analysing the calculation results for steels 20, 65G, and 40X (Fig. 2), it can be stated that the hydrogen concentration in the prefracture zone significantly depends on hydrostatic stress, which in turn depends on the mechanical properties of the material.

Tabela 1. Właściwości mechaniczne badanych stali i odpowiadające im maksymalne stężenie wodoru w strefie wstępnego pękania

Table 1. Mechanical properties of the studied steels and the corresponding maximum hydrogen concentration in the prefracture zone

Steel	σ_T, MPa	σ_B, MPa	σ_T/σ_B	$C_{H\,max}/C_0$
Steel 20	330	520	0,64	1,19
65G	525	980	0,54	1,4
40X	850	950	0,89	1,76
22К	260	500	0,52	1,18
16GNM	400	560	0,71	1,45
X70	695	733	0,95	1,75

Using the above values of $C_{H\,max}$ (Fig. 2), we constructed the dependence of the maximum relative hydrogen concentration in the prefracture zone on the value of σ_T/σ_B (squares in Fig. 3). This dependence is practically linear and is well described by the relationship $C_{H\max} \approx C_0\left(0,5+1,4\sigma_T/\sigma_B\right)$ (line in Fig. 3) for the range of values $0,4 < \sigma_T/\sigma_B < 1$. For further verification, calculations were performed for three more steels (22K, 16GNM, X70) with other values of σ_T, σ_B. The results in the graph are marked with circles.



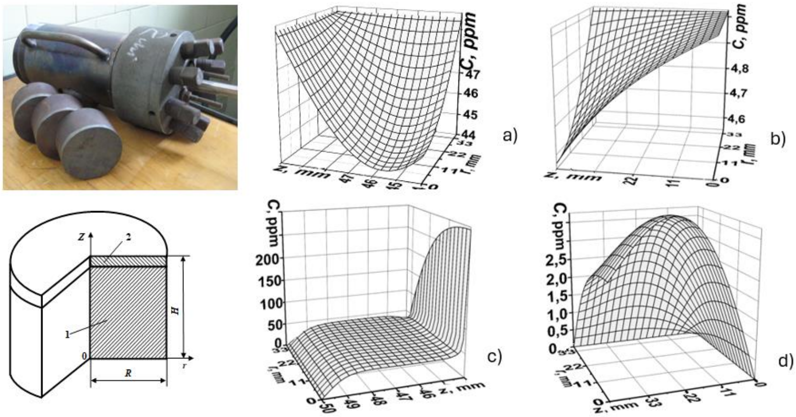
Rys. 3. Zależność maksymalnego względnego stężenia wodoru od właściwości mechanicznych materiału[8]

Fig. 3. Dependence of the maximum relative concentration of hydrogen on mechanical properties of material [8]

Therefore, having such a dependence (Fig. 3), it is possible for steels with a different value of σ_T to approximately estimate the maximum hydrogen concentration in the zone of prefracture in the loaded material.

4. Modeling the kinetics of hydrogen redistribution in bimetallic compounds

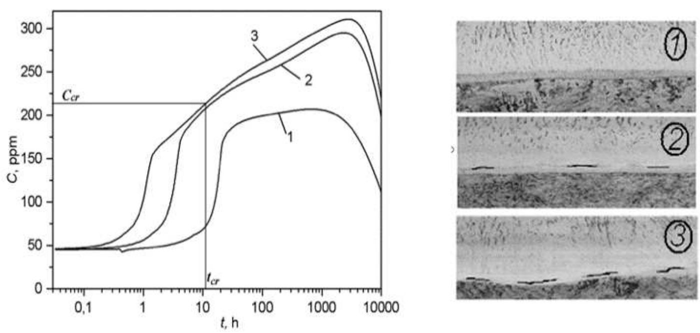
Further calculations provided the distribution of hydrogen concentration in a cylindrical specimen with a weld overlay due to high-temperature hydrogenation and subsequent cooling at different rates (Fig. 4) [14-17]. It was shown that in the fusion zone on the overlay side, areas of supersaturated hydrogen accumulation arise, which can lead to delamination of the overlay from the base metal. The extent of this supersaturation depends on the speed of thermal processes.



Rys. 4. Rozkład stężenia wodoru w powłoce (a, c) i metalu nieszlachetnym (b, d) po uwodornieniu w wysokiej temperaturze (a, b) i po 800 godzinach od rozpoczęcia chłodzenia z szybkością 100°C/h (c, d).

Fig. 4. Distribution of hydrogen concentration in the overlay (a, c) and the base metal (b, d) after high-temperature hydrogenation (a, b) and after 800 hours from the start of cooling at a rate of 100°C/h (c, d)

These studies determined the critical hydrogen concentration for the integrity of a bimetallic joint (Fig. 5).



Rys. 5. Zmienność w czasie maksymalnego stężenia wodoru i mikrostruktury strefy stopienia próbek bimetalicznych (x200) przy różnych szybkościach chłodzenia (1 - 20°C/h; 2 - 100°C/h; 3 - 300°C/h)

Fig. 5. Time variation of the maximum hydrogen concentration and microstructure of the fusion zone of bimetallic samples (x200) at different cooling rates (1 – 20°C/h; 2 – 100°C/h; 3 – 300°C/h)

Having determined from the experiment the moment of crack formation, we took the calculated hydrogen concentration corresponding to the given time at the damage site as critical. This is confirmed by the results of metallographic analysis (Fig. 5). At a cooling rate of 20°C/h, the maximum value of the hydrogen concentration does not exceed the critical value, and accordingly, there is no delamination in the samples. At higher cooling rates, when the maximum concentration exceeds the critical one, delamination of the weld deposit from the base metal is observed. Moreover, the higher the hydrogen concentration, the larger the delamination area.

5. Summary

Mathematical modeling is an important tool for studying the strength of structural elements in hydrogen and its mixtures. It enables the prediction of hydrogen's impact on materials, assessment of hydrogen embrittlement and corrosion failure risks, and optimization of structural solutions to enhance the longevity and reliability of engineering systems. The use of numerical methods and computational modeling significantly reduces the need for expensive experimental studies, facilitating the rapid development of hydrogen storage, transportation, and utilization technologies.

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MODELOWANIE MATEMATYCZNE W BADANIACH WYTRZYMAŁOŚCI ELEMENTÓW KONSTRUKCYJNYCH W ATMOSFERZE WODORU I JEGO MIESZANIN

Streszczenie

Niniejszy rozdział przedstawia kompleksowe badanie matematycznego modelowania zachowania materiałów konstrukcyjnych pod wpływem wodoru i jego mieszanin. Motywacja wynika z wyzwań związanych z kruchością wodorową i degradacją wytrzymałości metali, które są kluczowymi kwestiami dla rozwoju niezawodnej infrastruktury energii wodorowej. Autorzy opisują ramy modelowania, które obejmują transport wodoru, degradację mikrostrukturalną oraz ustalenie zależności między wytrzymałością mechaniczną a stężeniem wodoru. Szczególną uwagę poświęcono rozróżnieniu między wodorem dyfundującym i uwięzionym oraz roli pól naprężeń w redystrybucji wodoru. Obliczenia przeprowadzono dla różnych rodzajów stali w celu oceny stężenia wodoru w pobliżu wierzchołków pęknięć i koncentratorów naprężeń. Rozdział obejmuje również modelowanie kinetyki redystrybucji wodoru w spoinach bimetalicznych, pokazując krytyczną rolę szybkości chłodzenia w lokalnym przesyceniu i ryzyku rozwarstwienia. Eksperymentalna walidacja jest zapewniona poprzez analizę metalograficzną i symulacje numeryczne. Zaproponowane modele pozwalają na oszacowanie krytycznych stężeń wodorui ocenę ryzyka awarii w złożonych systemach materiałowych, przyczyniając się do projektowania bezpieczniejszych komponentów do przechowywania i transportu wodoru. Badanie potwierdza skuteczność modelowania matematycznego jako narzędzia predykcyjnego do oceny trwałości i zapobiegania awariom strukturalnym w środowiskach narażonych na działanie wodoru.

Słowa kluczowe: kruchość wodorowa, dyfuzja wodoru, degradacja wytrzymałości, uwięziony wodór, spoiny bimetaliczne, mechanika pękania, modelowanie matematyczne, materiały konstrukcyjne

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Tomasz LIS[2]

HYDROGEN IN AVIATION

Faced with the growing challenges of climate change, the aviation industry is intensively searching for alternative, more sustainable energy sources. Due to its properties, a promising candidate for the fuel of the future is hydrogen, particularly liquid hydrogen, which could have an impact on the decarbonization of the aviation sector. The chapter presented here is a review and focuses on issues related to the feasibility of hydrogen as an alternative fuel for the civil aviation sector, analyzing both the potential benefits and challenges of its implementation. The purpose of the chapter is to identify key issues related to the implementation of hydrogen as an alternative fuel for turbine jet engines powering today's aircraft. This paper presents the current state of knowledge on liquid hydrogen-powered aircraft technology, analyzing its technological progress. The paper also addresses the problem of toxic exhaust emissions produced during the combustion of fossil fuels, analyzes the environmental impact of hydrogen, discusses selected hydrogen properties, and storage technologies. The properties of hydrogen are compared with conventional aviation fuel. The chapter also focuses on the challenges posed to air transportation by the potential use of hydrogen fuel, while considering its advantages and disadvantages.

Keywords: aviation, aircraft propulsion, alternative fuels, cryogenic fuel, liquid hydrogen

1. Introduction

Hydrogen is seen as an alternative fuel for air transportation that will eliminate carbon dioxide (CO_2) emissions and thus contribute to the sustainability of air transportation, as well as provide long-term energy security based on renewable energy sources. Reducing greenhouse gas emissions is one of the key challenges in developing future commercial aircraft. Although hydrogen is used on a large scale in industries such as the chemical industry (ammonia production), petrochemical industry, its use as a fuel in aircraft turbine engines still poses a major technical challenge.

Contributing to this are the properties of hydrogen, which will have a direct impact on airframe structure, propulsion system components as well as ground infrastructure and logistics [24].

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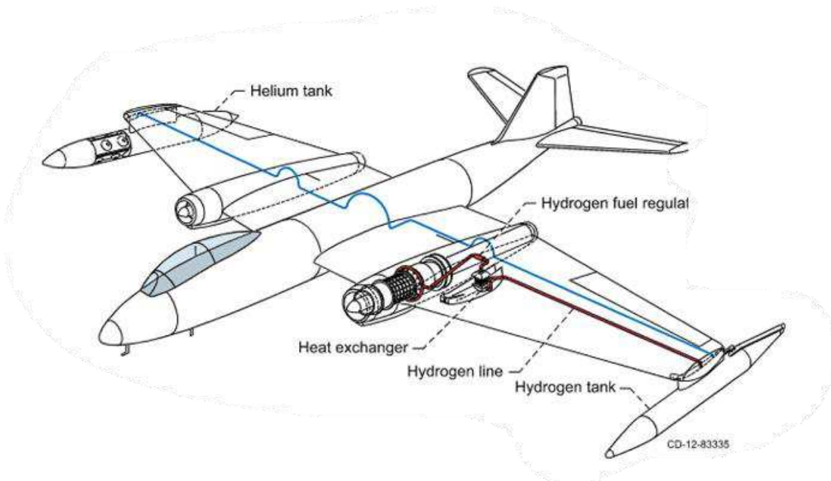
Although hydrogen has a high energy content per unit mass, its energy content per unit volume is low. This poses significant technical challenges, especially for on-board hydrogen storage [10].

2. Research on the possibility of implementing hydrogen in the aviation sector

Interest in hydrogen as an alternative fuel for aircraft turbine engines dates back to the 1950s. Even then, the first research work was being conducted, on the possibility of using hydrogen as an aviation fuel, which culminated in flight tests. The first flight of a hydrogen-powered aircraft took place in 1957. It was a twin-engine Martin B-57 Canberra bomber (Fig.1), equipped with J65 jet engines. One of the engines was adapted to burn both conventional jet fuel and hydrogen. To reduce the volume of hydrogen carried on board, the engines were fueled with conventional JP-4 fuel during takeoff and climb, while for high-altitude operations, the modified engine used hydrogen [8]. The hydrogen was stored in a liquid state in a dedicated tank located under the left wing (Fig.2) [5]. The amount of hydrogen carried in the tank, allowed the propulsion unit to operate for 21 minutes. The fuel control system was compatible with both JP-4 and hydrogen fuel [8]. The diagram of the hydrogen fuel system of the Martin B-57 aircraft is shown in the Fig.3.

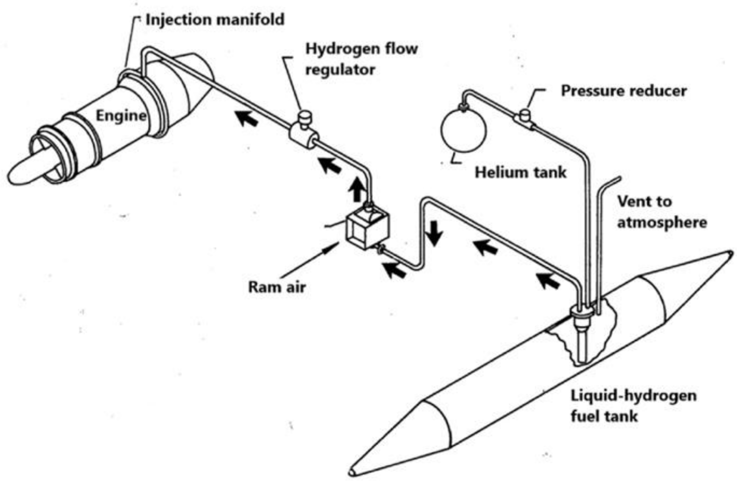
Rys. 1. Project Bee (zmodyfikowany samolot Martin B-57B Canberra) [11]

Fig. 1. Project Bee (Martin B-57B Canberra modification) [11]



Rys. 2. Bombowiec B-57 ze zmodyfikowanym układem paliwowym [24]

Fig. 2. B-57 bomber with a modified fuel system [24]



Rys. 3. Wodorowy układ paliwowy samolotu B-57 [24]

Fig. 3. Hydrogen fuel system for B-57 aircraft [24]

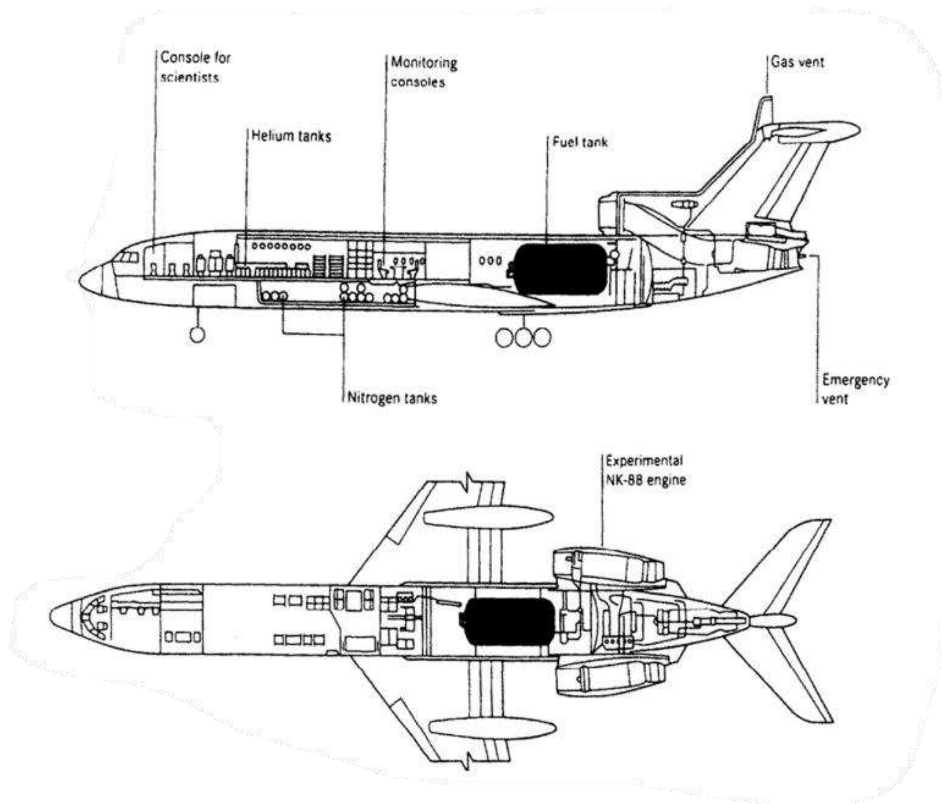
The B-57 aircraft made three test flights. During the first flight, from the climb to cruise phase, it was necessary to manually perform eight fuel tank venting operations, carried out by the flight engineer. This procedure led to pressure fluctuations inside the tank. The largest pressure drop of about 52% was recorded between the first and second venting. In subsequent test flights, this problem was solved by using a pump located at the bottom of the tank. Its task was to maintain a constant absolute discharge pressure of 3.65 bar. The flight tests were an undeniable success, confirming the reliable operation of the propulsion unit.

Work on the cryogenic-fueled aircraft was also carried out in the Soviet Union by the Tupolev Design Bureau, under the supervision of Vladimir Andreyev. The construction of the TU-155 aircraft was preceded by a multi-year research program to test the operation of more than 30 new systems. A three-engine aircraft, the TU-155 (Fig. 4) was built on the basis of the serial TU-154B aircraft, equipped with Kuznetsov NK-8 engines. The right engine (Fig.5), designated NK-88, was adapted for burning hydrogen [20]. The aircraft made its first flight using liquid hydrogen on April 15, 1988.

Rys. 4. TU-155 – modyfikacja pasażerskiego Tu-154 [29]

Fig. 4. TU-155 - modification of passenger Tu-154 [29]

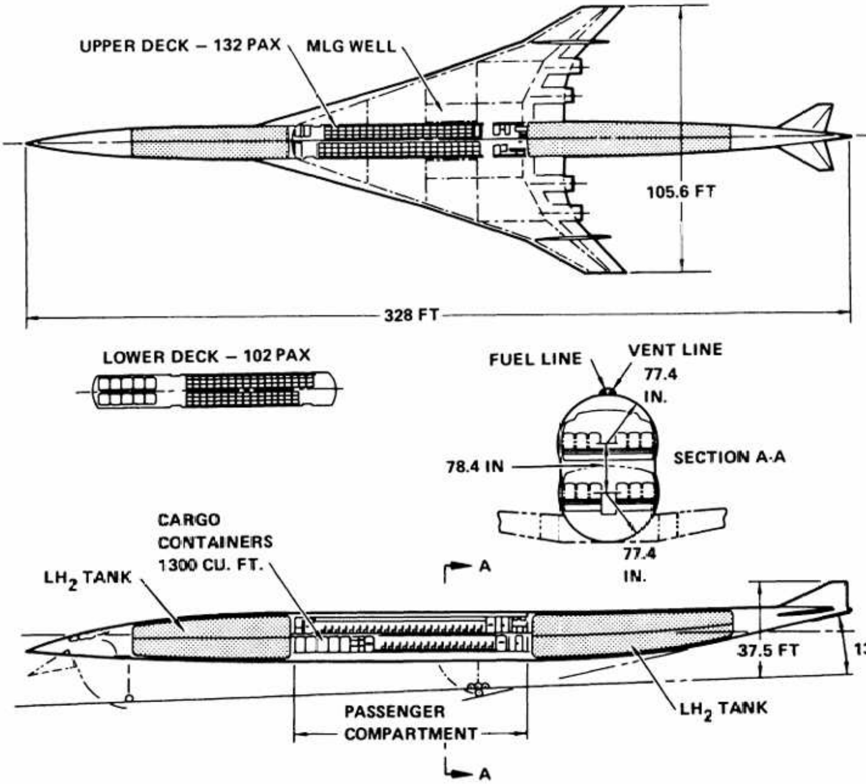
The cryogenic fuel tank, with a capacity of 17.5 m^3, was located in the rear of the fuselage (Fig.5), just forward of the power unit [24]. The other two engines, ran on conventional aviation fuel [30]. It is noteworthy that the fuel tank positioned in this way significantly reduced the possibility of using the interior space of the fuselage for cargo. The aircraft made more than a hundred flights, but only five used hydrogen as fuel. The TU-155 was adapted not only to use liquid hydrogen, but also liquefied natural gas (LNG), which gave it the status of the world's first cryogenic aircraft. The first LNG flight test was conducted on January 18, 1989. Experimental flights were planned to continue until 1997, but the project was canceled as a result of the collapse of the Soviet Union. The aircraft is stored at Zhukovskiy Airport, Moscow Region, Russia [25][17].



Rys. 5. Schemat zmodyfikowanego samolotu TU-155. Widoczny znacznych rozmiarów zbiornik wewnętrz kadłuba [24]

Fig. 5. Schematic of a modified TU-155 aircraft. Large internal fuselage tank visible [24]

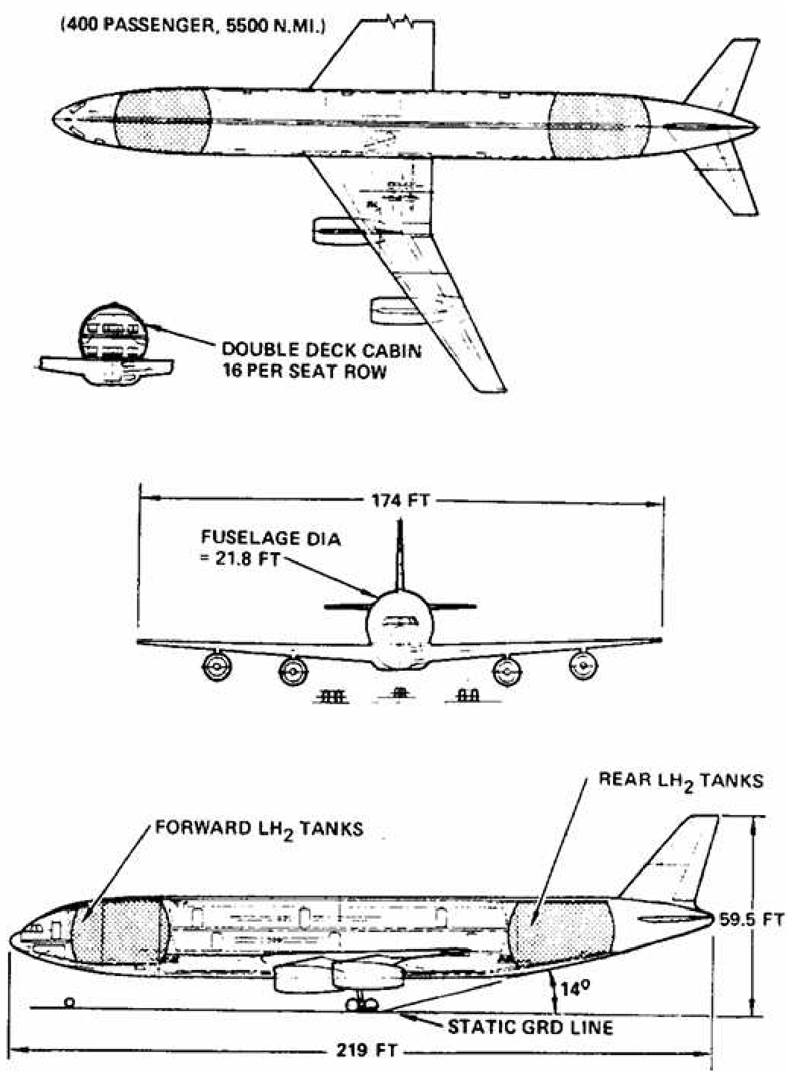
In 1972, the Lockheed California Company, in cooperation with NASA, began investigating the use of liquid hydrogen (LH_2) as a fuel for transport aircraft. Both subsonic and supersonic aircraft designs were analysed, the results of which are presented, among others, in G.D. Brewer's paper "Aviation usage of liquid hydrogen fuel - prospects and problems". In the supersonic variant of the aircraft (Mach number equal to 2.7), a two-level cabin was designed, located between the liquid hydrogen tanks, which were located in the front and rear of the fuselage [4]. This configuration had favourable mass and aerodynamic parameters, but need to move the fuel tanks from the wings to the inside of the fuselage, affected the length of its structure. The layout of a supersonic aircraft (Mach numer 2,7) is shown in Fig. 6.



Rys. 6. Układ samolotu naddźwiękowego zasilanego LH_2 [5]

Fig. 6. General arrangement of supersonic aircraft fueled by LH_2 [5]

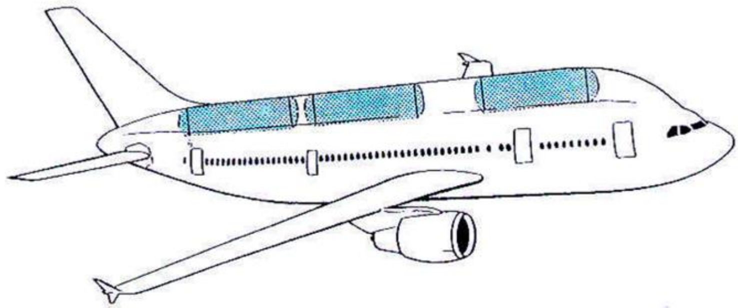
In the subsonic aircraft variant (Mach number of about 0.85), liquid hydrogen tanks were placed in the upper part of the fuselage above the cargo compartment. This variant was designed to carry 400 passengers. The double-deck passenger compartment was placed between the liquid hydrogen tanks [4]. The general layout of the configuration of a subsonic passenger aircraft fueled by liquid hydrogen is shown in Fig.7 [5]. The arrangement of the passenger compartment relative to the fuel tanks is very similar to the arrangement proposed for supersonic aircraft, with the difference that in the subsonic configuration the fuselage has a circular cross-section [4].



Rys. 7. Układ samolotu poddźwiękowego zasilanego LH_2 [4]

Fig. 7. General arrangement of subsonic aircraft fueled by LH_2 [4]

Today, climate change is a global and long-term problem, so interest in hydrogen-powered aircraft remains. The Cryoplane project, launched in 2000 and funded by the European Commission, was the first large-scale effort to explore the possibilities offered by the introduction of hydrogen-powered aircraft. One of the concepts developed as part of the project is shown in Fig.8 [1].



Rys. 8. Koncepcja samolotu wodorowego – Cryoplane project [31]

Fig. 8. Hydrogen aircraft concept – Cryoplane project [31]

In 2020, Airbus initiated the ZEROe project, which aims to bring the first hydrogen-powered passenger aircraft to market by 2035 [6][27][28]. However, due to the slow pace of development of key technologies, the company has confirmed that the deployment of such an aircraft will not occur before the end of 2040 [22][27]. The concept of an aircraft directly powered by liquid hydrogen is shown in Fig.9.

Rys. 9. Rys.7. Koncepcja samolotu zasilanego wodorem firmy Airbus [2]

Fig. 9. Airbus hydrogen-powered aircraft concept [2]

Alternatively, hydrogen also opens up opportunities for fuel cells, enabling the development of new configurations such as distributed electric propulsion. All-electric battery-powered aircraft have the potential to eliminate emissions on short regional routes, but battery performance is currently too low for long-range applications [1].

In 2024, the UK Civil Aviation Authority launched the Hydrogen Challenge project. The aim of this project is to prepare the UK aviation sector for the transition to zero carbon fuel. The initiative includes work on new aircraft designs and unmanned systems powered by hydrogen fuel cells. Particular attention will also be given to the necessary changes to the infrastructure that will enable the safe storage and refueling of hydrogen, as well as the organization of test flights and the analysis of safety aspects [32].

3. Prospects for hydrogen use in aviation

Hydrogen, symbolized by H and having an atomic number of 1, is the lightest chemical element, widely distributed in the universe. Depending on the temperature, hydrogen can occur in three states of aggregation: gas, liquid and solid [21]. Hydrogen is a colorless and odorless gas, flammable in a wide range of concentrations, ranging from 4% (lower flammability limit) to 75% (upper flammability limit) by volume in air. Hydrogen ignition occurs when the hydrogen concentration in the air is between the lower and upper flammability limits, in the presence of an ignition source, such as a spark. The flammability range of hydrogen is even wider in a mixture with pure oxygen [18]. The low value of the minimum ignition energy - 0.017 mJ - combined with wide flammability limits, means that hydrogen can be ignited relatively easily [21].

Hydrogen properties such as high diffusivity, low molecular weight and low viscosity mean that hydrogen easily leaks through small cracks and welds, and additionally, in contact with an improperly selected material, it can cause the so-called "hydrogen embrittlement", leading to cracking of e.g. tanks and, consequently, to hydrogen leakage [14]. For this reason, it is necessary to use highly sensitive hydrogen detection sensors, which will increase the safety of use and minimize economic losses [3].

The energy content of hydrogen per unit mass is almost 2.8 times higher than that of jet fuel (Tab.1). The higher gravimetric energy value reduces the total mass of the fuel, increasing the range of the flight [16][19]. Since hydrogen is a gas under normal conditions, its energy density per unit volume is low compared to liquid fossil fuels. This problem can be solved by liquefying and storing hydrogen in the liquid state, below the critical temperature.

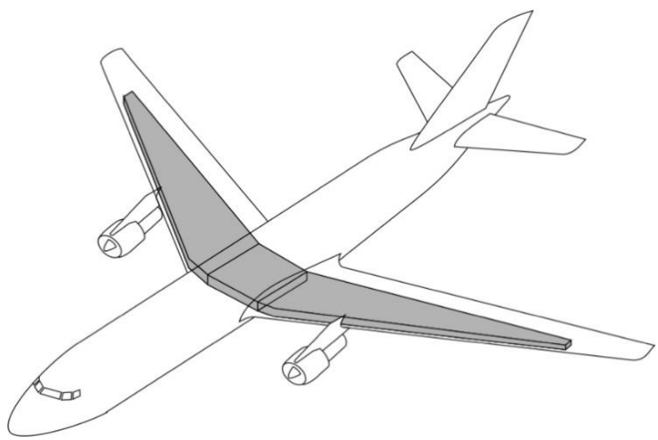
Compared to aviation kerosene, liquid hydrogen is characterized by a four time lower energy density per unit volume. This means that to store the same amount of energy, tanks with a four time larger volume are necessary. The increased size and weight of fuel tanks will result in a change in the airframe configuration. Finding the right space to store tanks will be one of the key challenges facing the aviation sector [10]. Selected properties of hydrogen are presented in the Table 1.

Tabela (tablica) 1. Wybrane właściwości ciekłego wodoru i nafty lotniczej [13][1]

Table 1. Selected properties of LH_2 and kerosene [13][1]

Property	Unit	Hydrogen	Kerosene
Lower Heating Value	MJ/kg	120	43,2
Energy density	MJ/L	8,5	34,9
Boiling Point	K	21	423-573
Cooling capacity	MJ/kg	20,2	0,38-0,85
Flame speed	m/s	2,67	0,39
Freezing point	K	13	223
Density at 1 atm	kg/m^3	70,8	802
Volumetric energy density	MJ/m^3	8,48	33,7

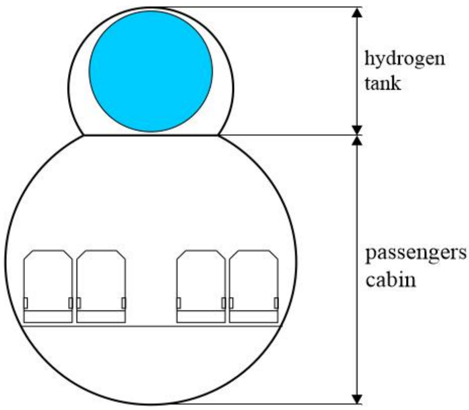
The existing fuel tank solutions, which in aviation are mainly located in the wings, cannot be used for high-pressure hydrogen or hydrogen in the liquid phase. Tanks for conventional liquid fuels have a form similar to cuboids, the walls of which are approximately flat surfaces and very often also constitute elements of the wing structure – so-called integral tanks (Fig.10).



Rys. 10. Zbiorniki nafty w skrzydle – nierealne rozwiązanie dla wodoru

Fig. 10. Wing kerosene tanks - unreal solution for hydrogen

In the case of hydrogen, these elements must be replaced with spherical or cylindrical tanks, which are characterized by high strength at high internal pressures with the lowest possible weight. The strongly curved shells of these tanks cannot be integral elements of the airframe. Placing spherical or cylindrical tanks with hydrogen inside the wing structure will significantly reduce their volume. The problem is particularly important due to the fact that hydrogen has a much lower density per unit volume compared to aviation kerosene. Therefore, it requires a four times larger tank capacity. Therefore, assuming the aircraft's range remains unchanged compared to solutions based on aviation kerosene, placing the main tanks in the wings is not possible. The only solution to this problem seems to be moving the tanks to the space inside the fuselage. However, in the case of transport aircraft, such a modification should not limit the cargo space. A promising solution to this problem may be the use of a fuselage with a double bubble cross-section (Fig.11).



Rys. 11. Przekrój poprzeczny kadłuba w koncepcji podwójnego balonu (porównaj Rys.8)

Fig. 11. Cross-section of the fuselage in the dubble bubble idea (compare Fig.8)

This concept is a combination of two cylindrical tanks, one of which can be a pressure cabin and the other can be used as a hydrogen tank. This solution also has disadvantages. The basic ones include an increased cross-section of the fuselage, which on the one hand contributes to a significant increase in the aircraft's drag force and on the other increases the fuselage's mass. Removing a significant amount of fuel from the wing will also adversely affect the internal force curves (shear force and bending moment). Increasing the value of internal forces will result in the need to increase the cross-sections of the wing elements, which will contribute to the total increase in the mass of the entire structure. The above problems are perfectly acceptable and solvable at the current level of knowledge and experience. The issue of safety is different, especially in emergency situations.

The location of liquid fuel tanks in the wings is advantageous due to the large distances separating these tanks from the areas intended for crew and passengers. The fuel installations in this variant also bypass critical areas. This is an excellent protection for people in an emergency situation, when it is necessary to dump a significant amount of fuel in flight or in a situation of necessary evacuation -

already on the airport runway. Currently, there are no appropriate procedures or even experience regarding such situations.

In addition, liquid hydrogen must be stored in thermally insulated tanks that are constantly cooled. Liquid nitrogen is a commonly used cooling agent. As a result of absorbing heat from the environment, liquid hydrogen changes to a gaseous state – this phenomenon is known as boil-off). Evaporating hydrogen increases the pressure inside the tank, which is why it is necessary to use venting systems, safety valves and pressure control systems. To ensure safe use and storage of hydrogen, systems for detecting potential leaks are also necessary. Cryogenic liquid constantly boils and evaporates. Even with the use of advanced thermal insulation in tanks, this phenomenon cannot be completely eliminated [14]. Before liquid hydrogen enters the combustion chamber of a turbine engine, it must be previously heated in a heat exchanger [24].

It is predicted that hydrogen may be a safer fuel than conventional aviation fuel, because it is a gas about 14 times lighter than air, which means it can escape into the atmosphere without major harmful effects [16]. Moreover, compared to hydrocarbons, hydrogen is characterized by high diffusivity, which favors its good miscibility, turbulence and obtaining a homogeneous mixture. Additionally, low ignition energy allows reliable ignition of the fuel-air mixture [21].

The high diffusivity of hydrogen can also play a significant role in emergency situations. When hydrogen accumulated in tanks is released, it will disperse quickly in open spaces. However, situations can be dangerous when hydrogen leaking from a tank accumulates in closed spaces, within the fuselage of the aircraft. Therefore, it is very important for on-board systems to be equipped with hydrogen leak detection systems and ventilation systems. Since hydrogen is lighter than air, it will tend to accumulate in the upper parts of accessible spaces, and due to its flammability and explosiveness, it can pose a serious threat to passenger safety.

The combustion rate of hydrogen is much greater than that of aviation kerosene, so the combustion time is short, which results in less heat being transferred by the flame compared to a conventional aviation fuel flame [21].

Turbine aircraft engines based on direct hydrogen combustion require modification of combustion chambers and fuel injectors to adapt them to the specific properties of this fuel. The stoichiometric flame temperature, flammability limits, and flame speed of hydrogen differ significantly from those of conventionally used aviation fuels [10]. The wide flammability range reduces the risk of flame extinction and ensures safe operation in conditions far from stoichiometry. Compact flames create the possibility of reducing the dimensions of the combustion chamber, which will result in reduced cooling air demand due to the reduction of surfaces exposed to thermal loads [10]. Hydrogen is characterized by a higher laminar combustion velocity and a higher adiabatic flame temperature, which can lead to a greater risk of flashback [9][10][23]. The flashback phenomenon is associated with the movement of the flame front towards the fuel source, in this case the injectors, which can result in their damage.

Liquefied hydrogen is used in a wide range of industrial applications, such as refining hydrocarbon products, steel production, electronics and fertilizer production. Due to the advantages of hydrogen, its use in industry is becoming increasingly common. Detecting hydrogen leaks is a key issue that cannot be ignored. Hydrogen with oxygen in air creates a highly explosive mixture. Among the explosion groups separated in accordance with the ATEX directive, hydrogen belongs to group II C, which is the most explosive. Difficulties in detecting hydrogen leaks result from the fact that it is an odorless and colorless gas, and additionally, flame detection during combustion is difficult because it is characterized by low thermal radiation, so its detection is difficult even using infrared [3].

4. Aircraft engine emissions

In 2022, aviation contributed 2% to global carbon dioxide emissions. In recent decades, the growth of this greenhouse gas has been faster compared to modes of transport such as rail, road and maritime transport. Following the Covid-19 pandemic, carbon dioxide emissions from air transport amounted to around 800 million tonnes of CO_2 in 2022, which was around 80% of pre-pandemic emissions. In 2022, aviation emissions accounted for 3.8% - 4% of total greenhouse gas emissions in the European Union. Aviation is the second largest source of greenhouse gas emissions in the transport sector (right after road transport), accounting for 13.9% of emissions [7].

ICAO (International Civil Aviation Organisation) predicts that aviation emissions could triple by 2050 compared to 2015 [7]. In 2019, the EU launched the European Green Deal. In order to achieve ambitious climate goals, transport emissions will have to be reduced by 90% by 2025 compared to 1990 levels.

Emissions generated by aircraft engines at high altitudes affect the physical and chemical properties of the Earth's atmosphere. This increases the greenhouse effect, which is a major factor influencing climate change. The areas most exposed to the harmful effects of turbine engines include areas around airports and the upper stratosphere.

Conventional fuel used in jet aircraft engines is aviation kerosene, obtained by distillation of selected types of crude oil, with an average composition of $C_{12}H_{23}$ [26]. The most commonly used fuels are those produced in accordance with the standardized JET A and JET A-1 fuel specifications [12].

Carbon dioxide CO_2 and water vapor H_2O are natural products of combustion of hydrocarbon fuels. As a result of incomplete combustion of aviation fuel, products such as carbon monoxide CO, unburned hydrocarbons UHC, solid particles (mainly carbon), nitrogen oxides NO_x and sulfur oxides SO_2 are created [13]. The composition of exhaust gases and their quantity depends on the conditions of the combustion process [26]. Sulfur has toxic and corrosive properties, which can cause corrosion of the combustion chamber, turbine blades or steering systems. For this reason, its content in aviation fuel is limited [12]. Soot formation is influenced by the number of aromatics contained in the fuel, e.g. synthetic fuel contains fewer aromatics, which results in the formation of less soot [24].

The chemical equation for the combustion reaction of an aviation fuel mixture with the approximate formula $C_{12}H_{23}$ in oxygen can be written in the following form:

$$C_{12}H_{23} + 17{,}75\ O_2 \rightarrow 12\ CO_2 + 11{,}5\ H_2O \quad (1)$$

The equation (1) can be written as:

$$167\ kg\ C_{12}H_{23} + 568\ kg\ O_2 \rightarrow 528\ kg\ CO_2 + 207\ kg\ H_2O \quad (2)$$

Relating to 1 kg of aviation kerosene:

$$1\ kg\ C_{12}H_{23} + 3{,}40\ kg\ O_2 \rightarrow 3{,}16\ kg\ CO_2 + 1{,}24\ kg\ H_2O \quad (3)$$

By burning 1 kg of aviation kerosene with the formula $C_{12}H_{23}$ in 3.4 kg of oxygen, 3.16 kg of carbon dioxide and 1.24 kg of water vapor are obtained.

The equation for the combustion of hydrogen in oxygen:

$$H_2 + 0{,}5\ O_2 \rightarrow H_2O \quad (4)$$

The equation (4) can be written as:

$$2\ kg\ H_2 + 16\ kg\ O_2 \rightarrow 18\ kg\ H_2O \quad (5)$$

For 1 kg of hydrogen the equation (5) takes the form:

$$1\ kg\ H_2 + 8\ kg\ O_2 \rightarrow 9\ kg\ H_2O \quad (6)$$

When burning 1 kg of hydrogen in 8 kg of oxygen, 9 kg of water vapor is obtained. Carbon dioxide and unburned hydrocarbons are not produced in the combustion process, because hydrogen fuel does not contain carbon. In this case, the main product of the combustion process is water vapor, the emission of which, based on the presented stoichiometric equations of the combustion reaction, is much greater compared to aviation kerosene.

In the case of hydrogen fuel combustion, the product of combustion will also be nitrogen oxides, created due to high combustion temperatures, which cause the nitrogen to react with the oxygen contained in the air. Hydrogen combustion reduces the formation of nitrogen oxides by 50-70%, compared to conventional fuels such as aviation kerosene or SAF [24].

Both water vapor and carbon dioxide are classified as greenhouse gases. The greenhouse effect of water vapor at an altitude above 6 km exceeds that of carbon dioxide for the same number of molecules [15]. However, taking into account the time these greenhouse gases stay in the atmosphere, it turns out that the time water vapor stays in the stratosphere is from 6 to 12 months, while for carbon dioxide it is much longer and, depending on the altitude, can be over 100 years. In order to limit the impact of water vapor on the greenhouse effect and reduce the formation of condensation trails, it is necessary to appropriately adjust the cruising altitude of aircraft powered by hydrogen fuel. Studies show that the optimal flight altitude of such aircraft should be lower by about 2-3 km compared to the cruising altitude of modern aircraft [15].

5. Summary

The presented selected aspects of the use of hydrogen as a fuel in aviation, supported by tests of aircraft powered by hydrogen fuel, show that the use of hydrogen in aviation is promising and, above all, feasible. However, in addition to the indisputable advantages of hydrogen as a fuel, one should also expect difficulties in its use. The most important issues are listed below.

The potential of using hydrogen in aviation:

- no carbon dioxide emissions,
- high energy content per unit volume, which is why it has been used as a fuel in space programs,
- no emissions typical of burning conventional hydrocarbon fuels, such as carbon monoxide, soot, unburned hydrocarbons, sulfur dioxide,
- reduction of nitrogen oxide emissions,
- possibility of using hydrogen as a coolant (for cooling hot section engine components),
- possibility of obtaining hydrogen from renewable energy sources.

Despite its promising benefits, the use of hydrogen in aviation also poses some challenges:

- low energy density per unit volume (increased storage space),
- the need to develop a new aircraft configuration (making space for high pressure tanks),
- the efficiency of hydrogen fuel propulsion systems will require modification of the combustion system,
- storing hydrogen tanks in the aircraft requires technologically advanced hydrogen tanks adapted to store hydrogen in a liquid state,
- developing procedures in the event of emergency situations (evacuation, planning rescue operations),
- the tendency to leaks entails the need to use advanced hydrogen detection systems,

- currently, hydrogen production using renewable energy sources is expensive,
- further research is needed on hydrogen storage and direct use in turbine engines to ensure adequate range and operational efficiency,
- the potential use of hydrogen to reduce CO_2 emissions will be achieved when the hydrogen is sourced from renewable sources.

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WODÓR W LOTNICTWIE

Streszczenie

W obliczu rosnących wyzwań związanych ze zmianami klimatu, przemysł lotniczy intensywnie poszukuje alternatywnych, bardziej zrównoważonych źródeł energii. Ze względu na swoje właściwości, obiecującym kandydatem na paliwo przyszłości jest wodór, w szczególności wodór ciekły, który może mieć wpływ na dekarbonizację sektora lotniczego. Prezentowany rozdział ma charakter przeglądowy i koncentruje się na kwestiach związanych z wykonalnością wodoru jako paliwa alternatywnego dla sektora lotnictwa cywilnego, analizując zarówno potencjalne korzyści, jak i wyzwania związane z jego wdrożeniem. Celem rozdziału jest identyfikacja kluczowych zagadnień związanych z wdrożeniem wodoru jako alternatywnego paliwa dla turbinowych silników odrzutowych napędzających współczesne samoloty. W rozdziale przedstawiono aktualny stan wiedzy na temat technologii samolotów napędzanych ciekłym wodorem, analizując jej postęp technologiczny. W rozdziale poruszono również problem emisji toksycznych spalin powstających podczas spalania paliw kopalnych, przeanalizowano wpływ wodoru na środowisko, omówiono wybrane właściwości wodoru oraz technologie jego magazynowania. Właściwości wodoru porównano z konwencjonalnym paliwem lotniczym. rozdział koncentruje się również na wyzwaniach, jakie dla transportu lotniczego stwarza potencjalne wykorzystanie paliwa wodorowego, rozważając jednocześnie jego zalety i wady.

Słowa kluczowe: lotnictwo, napęd lotniczy, paliwa alternatywne, paliwo kriogeniczne, ciekły wodór

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HYDROGEN AS A FUEL ENABLING THE REDUCTION OF AIR POLLUTION ON THE EXAMPLE OF THE CITY OF RZESZÓW

Transport is a source of harmful atmospheric emissions. In urban areas, due to the high population density, these emissions are particularly harmful. A significant proportion of emissions is generated by public transport. Green transformation and sustainable economic development necessitate the reduction of emissions. In the case of public transport, which is largely based on fossil fuel vehicles, significant effects can be achieved by replacing the bus fleet. Replacement with electric vehicles is already taking place as a result of legislation. A future-oriented process with even greater environmental benefits is the ongoing replacement of fossil fuel vehicles with green hydrogen-powered vehicles. Based on data on the transport work of public transport in Rzeszów, determination of the potential environmental benefits obtained by replacing the bus fleet by 2040 was achieved. Computer simulations were carried out for two bus fleet replacement scenarios. First scenario involved replacement of conventional buses with hydrogen buses with unchanged electric fleet, and the second replacement of conventional buses with hydrogen and electric buses. In both cases, significant reductions in atmospheric CO_2 emissions were achieved. In the first scenario CO_2 emissions were reduced by almost 99%. In the second scenario, the potential benefits in terms of reduced CO_2 emissions were lower at 80%. Both scenarios showed the need to modernise depots and make the necessary investments. In first scenario, it is the construction of infrastructure related to hydrogen storage and refuelling. In second scenario, it is additionally the need to expand the electric bus charging facility.

Keywords: public transport, CO2 emissions, green hydrogen, energy consumption, energy mix

1. Introduction

Transport is an economic branch that contributes significantly to atmospheric emissions. In order to reduce the harmful effects of transport, various solutions are being introduced.

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One of solutions is emission standards for conventional vehicles, which are set lower with each iteration. The most recent is the Euro VII standard, which is due to take effect in 2026 [1]. However, emission standards alone are not enough, so electric, hybrid and hydrogen vehicles are being introduced. Hybrid vehicles are a transition step between conventional and electric vehicles. In the case of electric vehicles, the origin of the electricity used to charge the batteries is very important. In countries with a largely coal-based energy industry, the benefits of electric vehicles may be significantly reduced [2-4]. The future solution is vehicles using hydrogen, especially green hydrogen. In addition, hydrogen vehicles have the advantage of shorter refuelling times than charging times for electric vehicles. Internal combustion engines emit exhaust gases containing particulate matter, nitrogen oxides and volatile organic compounds. Hydrogen fuel cells produce only water vapour during operation, significantly reducing air pollution and associated health risks in urban environments.

The proper functioning city requires a well-functioning transport system to ensure adequate mobility for city residents. One way to reduce air pollution in a city is through public transport [5]. However, public transport is also a source of air pollution. Therefore, measures are being carried out to reduce the harmful environmental effects of public transport. These measures are part of the sustainable development of urban transport. These measures include the replacement of conventional bus fleet with electric and hydrogen vehicles. This chapter examines the impact of a green transition involving two scenarios for the replacement of bus fleets on CO_2 emissions and the demand for green hydrogen, based on data on public transport in Rzeszów.

2. Public transport in Rzeszów and its development programme

Public transport fleet in Rzeszów consists of 224 buses, 8% of which are electric. The rest are diesel or CNG buses. The structure of the fleet along with annual mileage and average energy consumption is shown in Table 1. These data were obtained from MPK Rzeszów (Municipal Transport Company in Rzeszów). The fuel consumption and average energy consumption shown in the table were determined for all buses of a given type. However, articulated buses account for 15% of the fleet, but their share of annual mileage is lower, which translates into a smaller impact on average energy consumption.

Buses serve 54 daytime routes, 17 of which run outside the city. There are also 3 night routes in Rzeszów.

As part of the modernisation of the bus fleet, the purchase of 20 hydrogen buses by MPK Rzeszów and the construction of a hydrogen refuelling station at the depot are planned for the next two years [6-8]. These measures would consolidate Rzeszów's place at the forefront of cities implementing a green transformation programme aimed at switching to hydrogen propulsion in the near future. At the moment (March 2025), hydrogen buses are used in very few cities in Poland [9-11]. Poznań has the largest fleet of these buses.

Tabela 1. Struktura floty i roczny przebieg, zużycie paliwa i średnie zużycie energii w 2023 roku

Table 1. Fleet structure and annual mileage, fuel consumption and average energy consumption in 2023

Fuel type	Number of vehicles	Fuel consumption	Mileage, [km]	Average energy consumption, [MJ/km]
Diesel	91	2,312,294 l	5,537,104	14.47
CNG	115	3,564,834 m^3	5,760,883	22.28
EV	18	684,363 kWh	459,159	5.37

3. Impact of changes in bus fleet stock structure on air pollution

Computer simulations were carried out to analyse the impact of changes in bus fleet structure on air pollution. The simulation studies assumed 2 scenarios. The first scenario assumes a gradual replacement of diesel and CNG buses by hydrogen buses, with a constant number of electric buses. The second scenario assumes the gradual replacement of diesel and CNG buses with electric and hydrogen buses. Both scenarios assume a constant annual number of vehicle kilometres travelled for the entire fleet over the period 2023 - 2040 equal to 12,000,000 km. Constant values were also assumed for the average energy consumption and CO_2 emissions characterising the different bus types. In both scenarios, a linear decrease in end-user CO_2 emissions of electricity production was assumed from a value of 597 kg CO_2/MWh in 2023 [12] to a projected value of 268 kg CO_2/MWh in 2040 [13]. Both scenarios assume the complete phase-out of diesel and CNG buses by 2040. The assumed annual mileage in 2023, the annual change in mileage and assumed annual mileage in 2040 for each bus type in both scenarios are shown in Table 2.

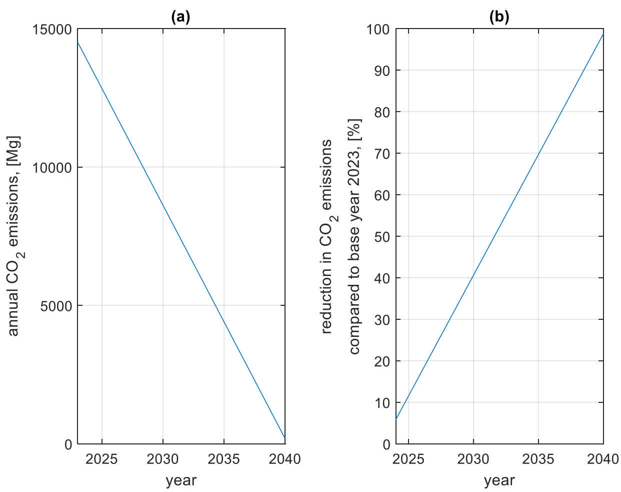
The simulation calculations carried out assumed a CO_2 emission factor for diesel of 3.138 kg / kg of fuel burned [14] and a CO_2 emission factor for CNG of 2.75 kg / kg of CNG burned [15]. A fuel consumption of 8.5 kg / 100km was assumed for hydrogen buses. This assumption is based on an analysis of the literature, where hydrogen consumption shows values between 5 and 10 kg / 100km [16-22]. Hydrogen was assumed to be green, because it is to be supplied to MPK Rzeszów [23], and therefore CO_2 emissions are 0 kg / kg hydrogen. An average of 330 days per year was assumed in which each bus performs work.

Tabela 2. Zakładany roczny przebieg w latach 2023 i 2040 oraz jego roczna zmiana według typu autobusu dla obu scenariuszy

Table 2. Assumed annual mileage in 2023 and 2040, and its yearly change by bus type for both scenarios

Bus type	Scenario 1			Scenario 2		
	Annual mileage in 2023 [km]	**Yearly change [km]**	**Annual mileage in 2040 [km]**	**Annual mileage in 2023 [km]**	**Yearly change [km]**	**Annual mileage in 2040 [km]**
CNG	5,780,000	-340,000	0	5,780,000	-340,000	0
Diesel	5,780,000	-340,000	0	5,780,000	-340,000	0
Electric	440,000	0	440,000	440,000	+340,000	6,220,000
Hydrogen	0	+340,000	11,560,000	0	+340,000	5,780,000
Total	12,000,000		12,000,000	12,000,000		12,000,000

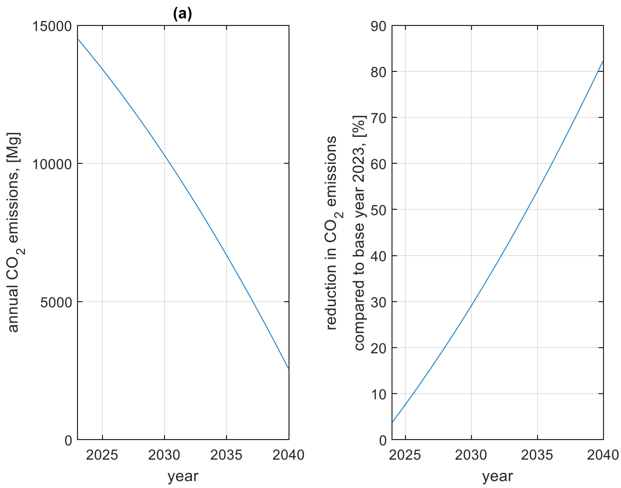
Figure 1 shows the projected annual CO_2 emissions and the reduction in CO_2 emissions compared to the base year of 2023 for Scenario 1. Figure 1 shows that it is possible to achieve a reduction in annual CO_2 emissions of more than 50% in 2032 and almost 99% in 2040 by replacing conventional buses with hydrogen buses. The remaining CO_2 emissions are due to the operation of electric buses, which are charged from power grid.



Rys. 1. Wynik scenariusza 1: (a) prognozowane roczne emisje CO2; (b) redukcja rocznej emisji CO2 w porównaniu do roku bazowego 2023

Fig. 1. Result of scenario 1: (a) projected annual CO_2 emissions; (b) reduction in annual CO_2 emissions compared to the base year 2023

Figure 2 shows the projected annual CO_2 emissions and the reduction in CO_2 emissions compared to the base year of 2023 for Scenario 2. Figure 2 shows that it is possible to achieve a reduction in annual CO_2 emissions of over 50% in 2035 and over 80% in 2040 by replacing conventional buses with electric and hydrogen buses. There is a noticeable difference from Scenario 1 due to the emissions associated with electricity generation.



Rys. 2. Wynik scenariusza 2: (a) prognozowane roczne emisje CO2;
(b) redukcja rocznej emisji CO2 w porównaniu do roku bazowego 2023

Fig. 2. Result of scenario 2: (a) projected annual CO_2 emissions;
(b) reduction in annual CO_2 emissions compared to the base year 2023

4. Analysis of the results of the considered scenarios

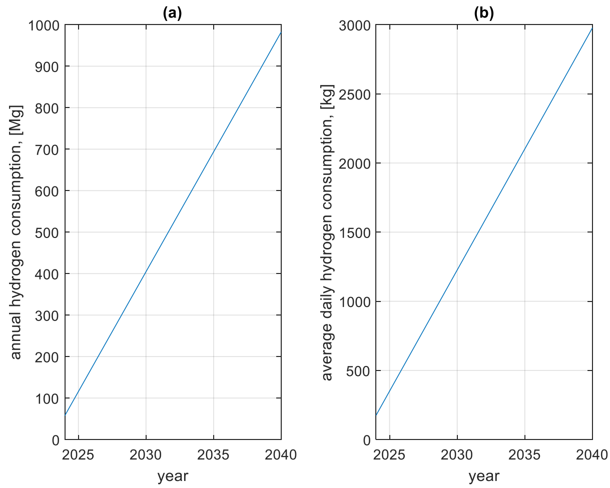
In both scenarios, CO_2 emissions to the atmosphere were reduced. Both scenarios indicate an increase in the consumption of hydrogen used to power buses. Depending on the scenario considered, the demand for hydrogen differs.

Figure 3 shows the annual hydrogen consumption and the average daily hydrogen consumption for the entire bus fleet for scenario 1.

Figure 4 shows the annual hydrogen consumption and the average daily hydrogen consumption for the entire bus fleet for scenario 2.

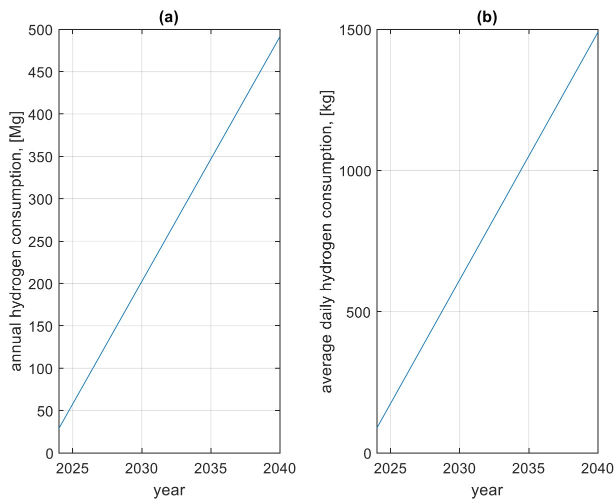
The implementation of any of the scenarios considered requires investment in hydrogen refuelling infrastructure. Scenario 1 is characterized by twice the demand for hydrogen and the need to provide distributors with twice the efficiency of the refuelling process. In scenario 1, in 2030 there is a need to ensure a refuelling capacity of over 1000 kg per day, as shown in Figure 3. However, in practice, buses are not refuelled around the clock. Most buses are refuelled after the end of the working day. Currently operating and planned hydrogen refuelling stations in Poland have a capacity of about 600 kg of hydrogen per day [24, 25]. This translates into the need for the capacity of at least 2 refuelling stations. In

2040, the capacity of at least 5 refuelling stations will be required to serve the bus fleet.



Rys. 3. Wynik scenariusza 1: (a) roczne zużycie wodoru dla całej floty autobusowej; (b) średnie dzienne zużycie wodoru dla całej floty autobusowej

Fig. 3. Result of scenario 1: (a) annual hydrogen consumption for the entire bus fleet; (b) average daily hydrogen consumption for the entire bus fleet



Rysunek 4. Wynik scenariusza 2: (a) roczne zużycie wodoru dla całej floty autobusów; (b) średnie dzienne zużycie wodoru dla całej floty autobusów

Figure 4. Result of scenario 2: (a) annual hydrogen consumption for the entire bus fleet; (b) average daily hydrogen consumption for the entire bus fleet

In scenario 2, at least 1 hydrogen refuelling station with a capacity of 600 kg per day will be required in 2030, and at least 3 hydrogen refuelling stations in 2040. Scenario 2 will also see an increase in the electric fleet. Therefore, In this scenario, an expansion of the charging infrastructure will be needed The current charging infrastructure for electric buses is adapted to the share of electric buses constituting less than 10% of the bus fleet. In scenario 2, this share will be about 50% in 2040. Such an increase in the number of electric buses will require investment in charging infrastructure.

5. Summary

In the chapter, simulation studies were conducted to analyse the impact of changes in the structure of public transport fleet on air pollution. Two scenarios were examined: replacing conventional buses with hydrogen buses and replacing conventional buses with hydrogen and electric buses. The results indicate that the second scenario is not sufficient to achieve zero-emission transport. This results from the expected electricity generation structure, in which fossil fuels will continue to have a significant share. In Poland, only hydrogen buses are a technology that can provide zero-emission public transport. The implementation of hydrogen fuel in public transport requires solving many technical and infrastructural problems. An appropriate distribution base for hydrogen fuel must be created, covering issues such as storage, transport and vehicle refuelling. A number of investments are also needed in the area of hydrogen production. The electrolysis process using electricity is also very important. Fully ecological green hydrogen can only be obtained through a process that uses energy from renewable energy sources or a nuclear power plant.

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WODÓR JAKO PALIWO UMOŻLIWIAJĄCE REDUKCJĘ ZANIECZYSZCZEŃ ATMOSFERY NA PRZYKŁADZIE MIASTA RZESZÓW

Streszczenie

Transport jest źródłem emisji szkodliwych substancji do atmosfery. W obszarach miejskich ze względu na dużą gęstość zaludnienia emisja ta jest szczególnie szkodliwa. Znaczna jej część jest generowana przez transport publiczny. Zielona transformacja i zrównoważony rozwój gospodarczy wymuszają ograniczenie tej emisji. W przypadku transportu publicznego, bazującego w większości na pojazdach wykorzystujących paliwa kopalne, znaczące efekty uzyskać można poprzez wymianę taboru autobusowego. W chwili obecnej taka wymiana na pojazdy o napędzie elektrycznym jest już prowadzona i wynika z przyjętego ustawodawstwa. Przyszłościowym i przynoszącym jeszcze większe korzyści ekologiczne jest rozpoczęty proces wymiany taboru wykorzystującego paliwa kopalne na pojazdy zasilane zielonym wodorem. Bazując na danych dotyczących pracy przewozowej komunikacji publicznej w Rzeszowie postanowiono określić potencjalne korzyści dla środowiska uzyskane poprzez wymianę taboru autobusowego do roku 2040. Do realizacji założonego celu wykorzystano symulacje komputerową przeprowadzoną dla dwóch różnych scenariuszy wymiany taboru autobusowego. W obu przypadkach uzyskano znaczące zmniejszenie emisji CO_2 do atmosfery. W przypadku pierwszego scenariusza zakładającego rezygnacje z dotychczasowego taboru autobusów o napędzie konwencjonalnym i zastąpieniu ich autobusami wodorowymi emisja CO_2 ograniczona został o prawie 99%. W scenariuszy tym stan taboru elektrycznego pozostał na niezmienionym poziomie. W drugim scenariuszu tabor konwencjonalny zastępowany był pojazdami elektrycznymi i wodorowymi. Potencjalne korzyści w postaci zmniejszenia emisji CO_2 były mniejsze i wynosiły 80%. Oba scenariusze wykazały konieczność przeprowadzenia modernizacji zajezdni i poczynienia niezbędnych inwestycji. W scenariuszu pierwszym to budowa infrastruktury związanej z magazynowaniem i tankowaniem wodoru. W scenariuszu drugim to dodatkowo konieczność rozbudowy instalacji ładowania autobusów elektrycznych.

Słowa kluczowe: transport publiczny, emisja CO2, zielony wodór, zużycie energii, mikst energetyczny

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FUEL CELLS IN AVIATION: LIMITATIONS, CAPABILITIES, AND DEVELOPMENT PROSPECTS

Contemporary geopolitical and climatic conditions pose numerous challenges for both science and the economy, particularly within the aviation sector. Recent years have underscored the necessity of exploring alternative energy sources and carriers that are less dependent on global supply chains and more resilient to the shifts of world politics and markets. One such carrier increasingly under consideration is hydrogen, with potential applications in aviation. A prime example is its use for onboard generation of electrical power to drive aircraft propulsion systems. This power can be produced via fuel cells. The present study outlines the principles of hydrogen-based propulsion systems employing fuel cells in aviation and identifies the associated limitations, capabilities, and future development prospects.

Słowa kluczowe: fuel cells, aviation, hydrogen, UAV

1. Introduction

The high availability of fossil fuels and the well-developed infrastructure for their use have, for decades, supported the maintenance of traditional aviation propulsion technologies without the need for significant changes. However, the fundamental physical and economic limitations of liquid fuel combustion—such as the low efficiency of converting chemical energy into mechanical work and the volatility of raw material costs—necessitate consideration of alternative energy sources [1]. Today's typical turbine engines achieve efficiencies of 40–50% under optimal conditions [2]. In the context of growing energy demand alongside the need to reduce mass and increase flight endurance, current technologies are approaching their developmental limits [3].

The increasing concentration of air traffic and the growing importance of aviation operations in environments with limited access to fuel infrastructure (e.g.,

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special-mission flights, regional aviation) call for energy sources that are more independent of global supply chains [4].

Moreover, the escalating climate crisis and global commitments to emissions neutrality mean that the civil aviation sector faces unprecedented technological, environmental, and regulatory challenges. According to data published by the International Civil Aviation Organization (ICAO), global aviation accounts for approximately 2.5% of total carbon dioxide emissions, with the actual climate impact potentially reaching 3.5% when accounting for nitrogen oxides (NO_x), aerosols, and contrail formation [5–8]. Unlike other modes of transport, aviation has limited electrification options due to critical requirements for mass, range, and reliability, making the search for alternative energy solutions particularly vital [9–12].

In this context, fuel-cell technologies—especially those powered by hydrogen—are the subject of intensive research and testing as a potential alternative to conventional fuels [13–15]. Key advantages of fuel cells include high efficiency (often exceeding 50% when fueled by hydrogen), low noise emissions, structural flexibility, and the potential for integration with hybrid systems [16–18]. Despite these numerous benefits, implementing fuel-cell technology in aviation applications faces several serious barriers. Chief among these are the low power and energy density per unit mass of the complete propulsion system (including tanks, balance-of-plant components, and thermal management systems), limited component durability under dynamically varying loads, and the complexity of integrating cooling, safety, and onboard hydrogen distribution systems [19,20]. Additionally, hydrogen storage—particularly in liquid or high-pressure form—presents material, energy, and certification challenges [21,22].

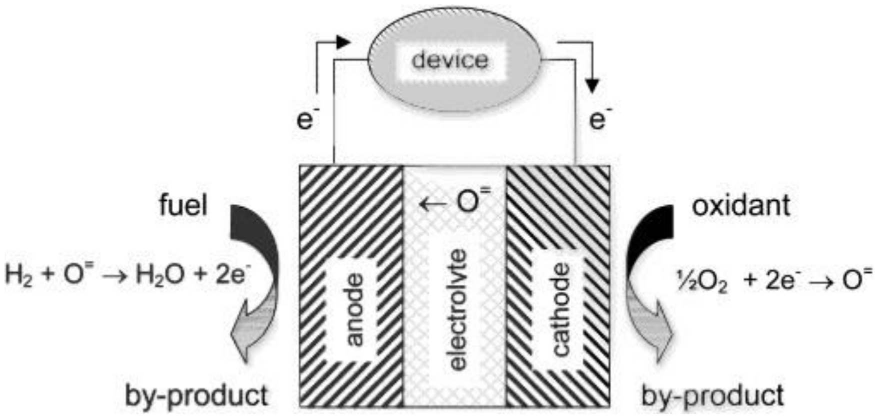
The aim of this chapter is to present a comprehensive and critical analysis of the potential for fuel cells in aviation. The authors have reviewed the current state of the technology, assessed technical and systemic barriers, and discussed development directions that may enable broader adoption of this technology over the coming decades. The goal of the analysis is to identify realistic pathways for implementing fuel-cell technology as a key component of sustainable aviation in the future.

2. Classification and operating principle of fuel cells

General characteristics of fuel cells

Fuel cells are advanced electrochemical energy converters that enable the direct conversion of the chemical energy of a fuel—most often hydrogen—into electrical energy, bypassing the traditional combustion process. Thanks to this direct conversion, fuel cells achieve higher energy efficiency and a significant reduction in pollutant emissions compared to conventional thermal systems such as internal combustion engines [23-27].

The basic components of a fuel cell include the anode, cathode, and electrolyte, as well as fuel and temperature management systems. In the electrochemical process, hydrogen supplied to the anode undergoes an oxidation reaction, releasing electrons and protons. The electrons travel through an external electrical circuit, thus generating electric current, while the protons migrate through the electrolyte to the cathode. There, they react with oxygen from the air to form water, which is the only by-product of this process [28,29]. Thanks to this unique characteristic, fuel cells offer the potential for clean energy production, which is critically important in the pursuit of more environmentally friendly energy technologies. The schematic in Figure 1 illustrates the construction of a fuel cell.



Rys. 1. Schemat ogniwa paliwowego składającego się z elektrolitu, anody i katody [30]

Fig. 1. Schematic of a fuel cell, comprised of an electrolyte, an anode and a cathode [30]

Fuel cells are capable of achieving high energy efficiency not only in transportation but also in stationary applications and as power sources across various industrial sectors. There is also potential for using other fuels, such as methane or ethanol, although hydrogen is considered the most promising material due to its properties and availability [31].

The performance and reliability of fuel cells during long-term operation depend on a number of key parameters that determine their functionality. The most important of these include:

- power density (W/kg or W/L): power density defines the amount of energy generated per unit of mass or volume of the cell [32];
- cell voltage: it plays a critical role in determining its efficiency – too low a voltage may result in lower energy conversion efficiency, while too high a voltage may lead to faster degradation of the cell materials;
- chemical-to-electrical conversion efficiency: this is a measure of the effectiveness of the process in which the chemical energy stored in the fuel is transformed into electrical energy – the higher the efficiency, the

less fuel is needed to generate a given amount of energy, which reduces operational costs and limits pollutant emissions [33];

- lifetime and cyclic durability: lifetime refers to the ability of the cell to operate over extended periods without significant performance degradation, while cyclic durability is the ability of the cell to maintain its performance after many start-stop cycles;
- load response dynamics: the ability of the cell to respond quickly to changes in load, i.e., energy demand;
- start-up capability: the time required to start the fuel cell and reach its full performance.

Start-up capability, compactness, and tolerance to environmental conditions determine the suitability of a given type of fuel cell for aviation applications [34].

Types of fuel cells

Fuel cells differ in both technology and application, depending on the type of electrolyte and the materials used for electrochemical reactions. There are several main types of fuel cells, each with its own unique characteristics, advantages, and limitations. Table 1 provides a synthetic overview of the key operational and design parameters of the six most popular fuel cell technologies, including operating temperature, efficiency, power density, start-up time, fuel type, advantages, limitations, and typical areas of application.

Tabela 1 Parametry operacyjne i konstrukcyjne sześciu najpopularniejszych technologii ogniw paliwowych [35-40]

Table 1 Operating and design parameters of the six most popular fuel cell technologies [35–40]

type of fuel cell	**PEMFC**	**DMFC**	**SOFC**	**AFC**	**PAFC**	**MCFC**
system efficiency [%]	40-55	40	40-60	60-70	40-50	50-60
stack power [kW]	1-100	0,001-100	0,5-2000	1-100	100-400	300-3 mln
operating temperature [°C]	60-110	70-130	500-1000	60-250	150-210	500-700
lifespan [hr]	2000-3000	1000-45000	1000	8000	>50000	7000-8000
cell voltage [v]	1,1	0,2-0,4	0,8-1,0	1,0	1,1	0,7-1,0
startup time	< 1 min	> 5 min	0,8-1,0	< 1 min	> 30 min	10 min

Tabela 1 Parametry operacyjne i konstrukcyjne sześciu najpopularniejszych technologii ogniw paliwowych [35-40]

Table 1 Operating and design parameters of the six most popular fuel cell technologies [35–40] (cont.)

type of fuel cell	**PEMFC**	**DMFC**	**SOFC**	**AFC**	**PAFC**	**MCFC**
fuel type	hydrogen	meyhanol	60 min	hydrogen, ammonia	hydrogen, methanol	natural gas, biogas, coal gas
advantages	small size; lightweight; quick startup time; quick load response; low temperature	low cost of fuel methanol; low operational temperature and pressure; high power density	high efficiency; fuel flexibility; solid electrolyte; suitable for CHP; hybrid/ gas turbine cycle	a wider range of stable materials allows components to be priced lower; low temperature; quick startup	suitable for CHP; increased tolerance to fuel impurities	fuel variety; high efficiency
Disadvant-ages	sensitivity to low temperature; sensitivity to humidity; sensitivity to salinity; sensitivity to fuel impurities	low reaction kinetics; methanol is very toxic; methanol is highly flamm-able	high temperature; long startup time; limited number of shutdowns; intensive heat	sensitive to CO_2 in fuel and air; electrolyte management (aqueous); electrolyte conductivity (polymer)	expensive catalysts; long startup time; sulfur sensitivity	slow response time; highly corrosive; low power density
applications	transportation; portable power; unmanned aerial vehicles	transportation; portable power; unmanned aerial vehicles	transportation; power plant; unman-ed aerial vehicles; auxiliary power units	transport; military; aerospace; auxiliary power units; off-grid telecom	building; utilities; distributed generation	utilities; distributed generation

3. Applications of fuel cells in aviation – current state

3.1. Overview of current projects

In recent years, there has been growing interest in the use of fuel cells in aviation, both in the civil and military sectors. These technologies align with global efforts toward decarbonizing transport and increasing the energy efficiency of propulsion systems. Below are selected ongoing projects:

- H2Fly – HY4: The German company H2Fly developed the HY4 technology demonstrator – a four-seat aircraft powered by PEMFC (Proton Exchange Membrane Fuel Cell) fueled by compressed hydrogen. In 2016, the first crewed flight using this propulsion took place, marking a breakthrough in crewed hydrogen applications [41].
- ZeroAvia – Dornier 228: The British-American company ZeroAvia is intensively working on a regional passenger aircraft with hydrogen propulsion. In January 2023, a Dornier 228 prototype equipped with PEMFC performed its first test flight with one electric motor powered by hydrogen [42].
- Airbus – ZEROe Concepts: Airbus presented three concepts for next-generation passenger aircraft powered by hydrogen. First commercial units are expected to enter operation around 2035 [43].

Experience with UAVs and smaller air platforms

Unmanned Aerial Vehicles (UAVs) serve as an important testing environment for fuel cell applications. Due to lower certification requirements and smaller propulsion system sizes, faster implementation and validation of new solutions are possible:

- HYCOPTER: UAV developed by HES Energy Systems, powered by a 1500 W fuel cell and has a maximum takeoff weight of 15 kg. It provides up to 3.5 hours of autonomous flight [44].
- Ion Tiger: UAV developed by the Naval Research Laboratory achieved a 24-hour flight time thanks to the use of high-efficiency PEMFC fuel cells [45].

4. Technological and system limitations

Mass and power density

One of the key limitations in the implementation of fuel cells in aviation is the low power and energy density compared to conventional turbine engines – considering the entire propulsion and fuel system. Although PEMFC fuel cells can achieve power densities up to 1 kW/kg, they still lag behind conventional solutions, where power density — for turbofan engines — typically amounts to about 7 kW/kg, and for turboprop engines about 5 kW/kg (including the entire propulsion and fuel system) [46]. Additionally, the use of compressed hydrogen tanks (700 bar) leads to a significant increase in the mass of the propulsion system and limits the available structural space [47,48].

Problems with hydrogen storage and distribution

Hydrogen storage remains a key challenge for fuel cell technology. Currently used methods — storage under high pressure (350–700 bar) or in liquid form (-253°C) — face engineering and cost issues. The main difficulties include:

- the need to use tanks made of advanced, expensive materials with high mechanical strength,
- increase in the total mass of the storage system,
- lack of developed hydrogen refueling infrastructure at airports [49,50].

Operating temperature and start/stop

High-temperature fuel cells (e.g., SOFC – Solid Oxide Fuel Cell, MCFC – Molten Carbonate Fuel Cell) are characterized by long start-up times, which limits their use in aviation where rapid operational readiness is required. Meanwhile, PEMFCs, despite their ability to start quickly, require complex cooling systems and maintenance of stable temperature conditions in the range of 60–80°C, which imposes additional design requirements [51–53].

Durability, reliability, and fuel cell life cycle

Currently available PEMFCs achieve durability of about 5,000–10,000 operating hours [54,55], which is insufficient for long-term use in commercial aviation. The problems include:

- degradation of the proton exchange membrane [56,57],
- corrosion of electrodes,
- decline in catalytic activity (especially Pt), which significantly affects system reliability and operational costs [58,59].

This necessitates the development of new materials and real-time diagnostic strategies for fuel cell condition monitoring.

5. Possibilities for development and research directions

In the context of further development of fuel cells in aviation, the following strategic research directions are identified:

- **new materials for electrodes and membranes:** Increasing durability and energy conversion efficiency requires the development of more resistant materials, especially catalysts with reduced platinum content and alternative membranes with enhanced chemical resistance [60,61].

- **integration with hybrid propulsion:** Combining fuel cells with batteries or gas turbines can increase operational flexibility and enable optimization of hydrogen consumption [62,63].
- **advanced energy and cooling management systems:** Dynamic management of power flow and temperature is a key element for efficient fuel cell operation under variable aviation conditions [64,65].
- **development of lightweight hydrogen tanks:** Composite type IV tanks, characterized by low weight and high strength, are a promising solution for reducing the overall mass of hydrogen storage systems [66,67].

6. Summary

The use of hydrogen propulsion systems based on fuel cells in aviation is still at an early stage of development and requires further research and development efforts. These studies should be regarded as important and promising. Hydrogen can be used to power aircraft as a fuel for generating electricity, which can then be used to drive, for example, electric motors or other onboard components. An advantage of this type of technology is, among other things, the possibility of producing hydrogen independently of global supply chains, as well as its very low environmental impact. At the same time, it should be noted that current hydrogen fuel systems are characterized by relatively high complexity and massiveness, and fuel cells are not yet adapted for long-term and intermittent operation.

For this reason, conducting research aimed at increasing the durability of fuel cells and reducing the mass of hydrogen fuel systems is considered very important, as is the analysis of the operational characteristics of hydrogen-powered aircraft. In parallel, research should be carried out on the integration of hydrogen propulsion systems with other types of propulsion, particularly hybrid systems, as well as on the management of the hydrogen propulsion-fuel system to ensure optimal operating conditions.

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OGNIWA PALIWOWE W LOTNICTWIE: OGRANICZENIA, MOŻLIWOŚCI I PERSPEKTYWY ROZWOJU

Streszczenie

Współczesne warunki geopolityczne i klimatyczne stawiają liczne wyzwania zarówno przed nauką, jak i gospodarką, w szczególności w sektorze lotniczym. Ostatnie lata uwypukliły konieczność poszukiwania alternatywnych źródeł I nośników energii, które są mniej zależne od globalnych łańcuchów dostaw i bardziej odporne na zmiany światowej polityki i rynków. Jednym z takich coraz częściej rozważanych nośników jest wodór, z potencjalnymi zastosowaniami w lotnictwie. Doskonałym przykładem jest jego wykorzystanie do generowania energii elektrycznej na pokładzie w celu napędzania systemów napędowych samolotów. Energia ta może być wytwarzana za pomocą ogniw paliwowych. Niniejsze opracowanie przedstawia zasady działania wodorowych układów napędowych wykorzystujących ogniwa paliwowe w lotnictwie oraz identyfikuje związane z nimi ograniczenia, możliwości i przyszłe perspektywy rozwoju.

Słowa kluczowe: ogniwa paliwowe, lotnictwo, wodór, UAV

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ZASTOSOWANIE WODORU W CHOROBACH NEURODEGENERACYJNYCH

Molekularny wodór (H_2) wykazuje właściwości antyoksydacyjne i przeciwzapalne, co czyni go potencjalnym środkiem terapeutycznym w leczeniu zaburzeń neurologicznych i psychiatrycznych. W ostatnich latach rosnąca liczba badań wskazuje na jego korzystny wpływ na układ nerwowy, szczególnie w kontekście neuroprotekcji oraz redukcji stresu oksydacyjnego. Celem niniejszej pracy jest przegląd aktualnych badań dotyczących zastosowania wodoru w terapii chorób ośrodkowego układu nerwowego. Przeprowadzono przegląd literatury z wykorzystaniem baz danych PubMed i Scopus, koncentrując się na badaniach z ostatnich 10 lat, które analizowały wpływ wodoru na choroby neurodegeneracyjne (takie jak choroba Alzheimera i choroba Parkinsona), depresję oraz inne zaburzenia psychiatryczne. Analiza literatury wskazuje, że wodór może wywierać działanie neuroprotekcyjne poprzez neutralizację wolnych rodników, modulację procesów zapalnych oraz poprawę funkcji mitochondriów. Badania kliniczne wykazały korzystne efekty podawania wodoru – szczególnie w formie inhalacji lub wody nasyconej wodorem – zwłaszcza w łagodzeniu objawów depresyjnych oraz poprawie funkcji poznawczych u pacjentów z chorobami neurodegeneracyjnymi. Molekularny wodór wydaje się obiecującą strategią terapeutyczną w leczeniu zaburzeń neurologicznych i psychiatrycznych. Jednak pomimo tych obiecujących wyników, konieczne są dalsze badania kliniczne w celu określenia optymalnych metod podawania oraz długoterminowej skuteczności terapii wodorem.

Słowa kluczowe: wodór molekularny, neuroprotekcja, stres oksydacyjny, choroby neurodegeneracyjne

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1. Wprowadzenie

Choroby neurodegeneracyjne, takie jak choroba Alzheimera (AD), choroba Parkinsona (PD) oraz stwardnienie zanikowe boczne (ALS), stanowią istotne wyzwanie dla współczesnej medycyny.

Charakteryzują się postępującą degeneracją neuronów, prowadzącą do zaburzeń poznawczych i motorycznych. Wraz ze starzeniem się populacji, ich rozpowszechnienie znacząco wzrasta. Według danych Światowej Organizacji Zdrowia (WHO), w 2019 roku na świecie odnotowano ponad 8,5 miliona przypadków choroby Parkinsona, co stanowi wzrost o 81% od 2000 roku [1]. Podobnie, liczba osób żyjących z chorobą Alzheimera i innymi rodzajami otępień wzrosła z 21,8 miliona w 1990 roku do 56,9 miliona w 2021 roku, co stanowi wzrost o 161% [2].

Patogeneza tych chorób jest złożona i wieloczynnikowa, jednak ważną rolę odgrywają w niej stres oksydacyjny oraz stan zapalny. Mózg, ze względu na wysokie zużycie tlenu i bogactwo wielonienasyconych kwasów tłuszczowych, jest szczególnie podatny na uszkodzenia oksydacyjne. Nadmierna produkcja reaktywnych form tlenu (ROS) prowadzi do uszkodzenia białek, lipidów oraz DNA, co skutkuje dysfunkcją i śmiercią neuronów [3]. Ponadto, aktywacja mikrogleju w odpowiedzi na stres oksydacyjny inicjuje kaskadę reakcji zapalnych, które nasilają uszkodzenia neuronalne [4]. Interakcja między stresem oksydacyjnym a neurozapaleniem tworzy błędne koło, przyspieszając progresję chorób neurodegeneracyjnych [5].

W ostatnich latach badania koncentrują się na zrozumieniu mechanizmów molekularnych leżących u podstaw tych procesów. Na przykład, dysfunkcja mitochondriów prowadzi do zwiększonej produkcji ROS, co z kolei aktywuje szlaki sygnałowe związane z zapaleniem, takie jak inflamasomy [6]. Zrozumienie tych mechanizmów jest kluczowe dla opracowania nowych strategii terapeutycznych, które mogłyby modulować stres oksydacyjny i stan zapalny w celu spowolnienia lub zatrzymania postępu chorób neurodegeneracyjnych.

2. Wodór jako cząsteczka biologicznie aktywna

Właściwości wodoru molekularnego (H_2)

Wodór molekularny (H_2) to najmniejsza i najlżejsza cząsteczka, zbudowana z dwóch atomów wodoru. Jest elektrycznie obojętna i niepolarna, dzięki czemu swobodnie dyfunduje przez błony komórkowe, błony organelli, a nawet barierę krew–mózg [7]. Właściwość ta pozwala wodoru na szybkie przenikanie do wnętrza komórek oraz docieranie do struktur wewnątrzkomórkowych, takich jak mitochondria, gdzie może przeciwdziałać uszkodzeniom oksydacyjnym [8].

Historia badań nad wodorem w medycynie

Pierwsze udokumentowane wykorzystanie wodoru w kontekście medycznym sięga końca XIX wieku, gdy Nicholas Senn zastosował wodór do wykrywania perforacji przewodu pokarmowego przez rektalne podanie gazu [9]. W kolejnych dekadach wodór pojawiał się w medycynie jako składnik mieszanek oddechowych, np. w nurkowaniu głębinowym oraz jako wskaźnik w pomiarach przepływu krwi [10]. Jednak dopiero badanie Ohsawy i współpracowników z 2007 roku zapoczątkowało erę medycyny wodorowej. Autorzy wykazali, że H_2 działa jako selektywny antyoksydant, redukując stres oksydacyjny i uszkodzenia neuronalne w modelu niedokrwienia–reperfuzji mózgu [11]. Od tego czasu liczba badań nad terapeutycznym zastosowaniem wodoru gwałtownie wzrosła [12].

Mechanizmy działania – głównie antyoksydacyjne i przeciwzapalne

H_2 działa ochronnie przede wszystkim poprzez mechanizmy antyoksydacyjne i przeciwzapalne. Bezpośrednio neutralizuje najbardziej szkodliwe wolne rodniki, takie jak rodnik hydroksylowy (•OH) oraz nadtlenoazotyn ($ONOO^-$), nie wpływając na fizjologiczne ROS, dzięki czemu nie zakłóca procesów komórkowych zależnych od redoksu [13]. Co więcej, wodór aktywuje szlaki ochronne, takie jak Nrf2, zwiększając ekspresję enzymów antyoksydacyjnych, np. SOD, katalazy czy hemooxygenazy-1 [14].

Pod względem działania przeciwzapalnego H_2 hamuje aktywację NF-κB – czynnika transkrypcyjnego odpowiedzialnego za ekspresję licznych prozapalnych cytokin (IL-1β, IL-6, TNF-α) [15]. Dzięki tym właściwościom wodór może działać neuroprotekcyjnie, szczególnie w chorobach o podłożu neurozapalnym i oksydacyjnym, takich jak AD czy PD [16].

3. Zastosowanie wodoru w chorobach neurodegeneracyjnych

1) Przegląd badań in vitro i in vivo (np. u zwierząt) – jak wodór wpływa na mózg i neurony
2) Wybrane choroby:
   - **Otępienie typu alzheimerowskiego** – wpływ wodoru na amyloid beta, stres oksydacyjny
   - **Choroba Parkinsona** – zmniejszanie uszkodzenia neuronów dopaminergicznych
   - **SLA / SM / inne** – mniej danych, ale obiecujące kierunki
3) Możliwości aplikacji – np. inhalacja wodoru, woda nasycona wodorem

4. Potencjał i ograniczenia zastosowania wodoru w szeroko pojętej medycynie.

Dlaczego wodór budzi nadzieję?

Wodór molekularny (H_2) zyskał miano obiecującej cząsteczki terapeutycznej dzięki swojej unikalnej zdolności do selektywnego neutralizowania najbardziej szkodliwych wolnych rodników bez zakłócania fizjologicznych procesów redoks. Jako najmniejsza znana i dostępna cząsteczka w przyrodzie, wodór z łatwością przenika przez błony biologiczne i dociera do struktur szczególnie wrażliwych na stres oksydacyjny, jak neurony. Dodatkowo, jego zdolność do modulowania szlaków zapalnych i aktywacji układów antyoksydacyjnych czyni go potencjalnym narzędziem w terapii chorób o podłożu neurozapalnym, takich jak choroba Alzheimera, Parkinsona czy wiele innych [17].

W badaniach przedklinicznych wodór wykazał działanie neuroprotekcyjne – zmniejsza agregację amyloidu beta, chronił neurony dopaminergiczne przed uszkodzeniami i obniżał poziom cytokin prozapalnych. Wstępne wyniki są na tyle obiecujące, że wodór coraz częściej pojawia się w literaturze jako potencjalny komponent terapii wspomagającej w procesach neurodegeneracyjnych [7,8].

Jakie są ograniczenia?

Pomimo wielu pozytywnych doniesień dotyczących zastosowanie wodoru w medycynie, wiele wciąż znajduje się na etapie badań eksperymentalnych. Jednym z głównych ograniczeń jest brak dużych, randomizowanych badań klinicznych z udziałem pacjentów cierpiących na choroby neurodegeneracyjne. Większość danych pochodzi z badań in vitro lub na modelach zwierzęcych, co utrudnia bezpośrednie przełożenie wyników na praktykę kliniczną.

Kolejnym wyzwaniem pozostaje ustalenie optymalnego sposobu podawania oraz dawkowania wodoru. Obecnie badane są różne formy aplikacji, takie jak inhalacja gazowego H_2, picie wody nasyconej wodorem czy dożylne podanie soli fizjologicznej wzbogaconej w H_2. Każda z tych metod różni się biodostępnością, czasem działania i potencjalną skutecznością, co wymaga dalszej standaryzacji [18,19].

Nie opisano także w pełni jasnego mechanizmu działania– mimo że znane są ogólne szlaki antyoksydacyjne i przeciwzapalne, nie wiadomo jeszcze, które z nich odgrywają kluczową rolę w danym typie neurodegeneracji. Istnieje też potrzeba zbadania interakcji wodoru z innymi lekami oraz określenia jego długoterminowego profilu bezpieczeństwa.

Co jeszcze trzeba zbadać?

- Badania kliniczne fazy II i III, obejmujące różne stadia chorób takich jak AD, PD czy ALS, z kontrolą placebo i długoterminową obserwacją.

- Standaryzacja formy i dawki wodoru – określenie, która droga podania jest najskuteczniejsza i najbardziej opłacalna w zależności od jednostki chorobowej.
- Biomarkery skuteczności – potrzebne są czułe wskaźniki, pozwalające obiektywnie ocenić efekty terapii wodorowej na poziomie komórkowym i funkcjonalnym.
- Interakcje z lekami konwencjonalnymi – zrozumienie, jak wodór wpływa na działanie innych leków stosowanych w neurologii co pozwoli wykluczyć ewentualne ryzyko powikłań polifarmakoterapii.
- Badania populacyjne – uwzględniające dostosowanie dawek i formy podania do odpowiedniej populacji w czym jest kluczowe poznanie indywidualnej odpowiedzi na terapię, np. wynikające z wieku, płci, stylu życia czy genotypu.

5. Perspektywy

Podsumowanie głównych wniosków

Zastosowanie wodoru molekularnego w terapii chorób neurodegeneracyjnych stanowi fascynującą i dynamicznie rozwijającą się dziedzinę badań. Jego niewielki rozmiar, zdolność do przenikania barier biologicznych oraz działanie antyoksydacyjne i przeciwzapalne czynią z niego potencjalne rozwiązanie dla nieuleczalnych chorób. Wstępne badania wykazały, że wodór może ograniczać stres oksydacyjny, zmniejszać stan zapalny i chronić neurony przed degeneracją – procesami wspólnymi dla wielu chorób neurologicznych.

Wskazanie potencjalnych kierunków badań

W przyszłości warto zwrócić uwagę na dotychczas pomijane obszary:

- Przełożeniu wyników badań przedklinicznych na modele kliniczne – w tym testowaniu wodoru jako terapii wspomagającej w leczeniu choroby Alzheimera czy Parkinsona.
- Opracowaniu innowacyjnych form podania wodoru – np. kapsułek z opóźnionym uwalnianiem, implantów generujących wodór in situ, czy połączeń z nanonośnikami.
- Zbadania korelacji terapii wodorowej z innymi podejściami, np. farmakoterapią, dietą przeciwzapalną, czy neurorehabilitacją.
- Sprawdzeniu działania wodoru w chorobach rzadkich lub mniej znanych, jak np. otępienie czołowo-skroniowe czy choroba Huntingtona co będzie stanowiło ogromne wyzwanie dla badaczy.

Dlaczego warto traktować wodór nie tylko jako paliwo, ale też jako potencjalny lek

Przez lata a szczególnie teraz postrzegamy wodór głównie jako – paliwo przyszłości. Jednak obecnie coraz więcej dowodów wskazuje, że jego potencjał sięga znacznie dalej. Możliwość wykorzystania tej popularnej cząsteczki w medycynie – zwłaszcza w kontekście stanowiących wielkie wyzwanie schorzeń, którymi są choroby neurodegeneracyjne – takie świeże spojrzenie może zrewolucjonizować nasze podejście do terapii. Być może przyszłość należy nie tylko do „zielonego wodoru” w kontekście energetyki, ale także do „terapeutycznego wodoru” w nowoczesnej medycynie.

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THE APPLICATION OF HYDROGEN IN NEURODEGENERATIVE DISEASES

S u m m a r y

Molecular hydrogen (H_2) exhibits antioxidant and anti-inflammatory properties, making it a potential therapeutic agent in the treatment of neurological and psychiatric disorders. In recent years, a growing body of research has suggested its beneficial effects on the nervous system, particularly in the context of neuroprotection and oxidative stress reduction. The aim of this paper is to review current studies on the application of hydrogen in the therapy of central nervous system diseases. A literature review was conducted using the PubMed and Scopus databases, focusing on studies from the last 10 years that explored the effects of hydrogen on neurodegenerative diseases (such as Alzheimer's and Parkinson's disease), depression, and other psychiatric disorders. The analysis of the literature indicates that hydrogen may exert neuroprotective effects by neutralizing free radicals, modulating inflammatory processes, and improving mitochondrial function. Clinical studies have shown beneficial effects of hydrogen administration—particularly in the form of inhalation or hydrogen-rich water— especially in alleviating depressive symptoms and enhancing cognitive function in patients with neurodegenerative conditions. Molecular hydrogen appears to be a promising therapeutic strategy in the treatment of neurological and psychiatric disorders. However, despite these encouraging findings, further clinical research is necessary to determine optimal delivery me hods and the long-term efficacy of hydrogen therapy.

Keywords: molecular hydrogen, neuroprotection, oxidative stress, neurodegenerative diseases

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PERFORMANCE AND SYSTEM EVALUATION OF A HYDROGEN-POWERED 12-METER URBAN BUS IN POLISH OPERATIONAL CONDITIONS

The chapter presents a comprehensive analysis of the key factors influencing the implementation of hydrogen as a fuel in urban public transport in Poland. Particular emphasis is placed on the regulatory framework governing the production and use of hydrogen in road transport, regarding to both national legislation and European Union directives supporting the development of hydrogen technologies. Chapter highlights the vital role of a coherent legislative and institutional environment as a prerequisite for the effective use of hydrogen within the public transportation sector. In parallel, the paper offers an in-depth assessment of the Polish energy market in the context of hydrogen production potential, emphasizing its increasing relevance in conjunction with renewable energy sources and the broader transition of the transport sector toward zero-emission solutions. Further, the chapter explores the current state and development trends of the domestic urban hydrogen-powered buses market, including an analysis of registration data over recent years, commercially offered models, and the refuelling infrastructure expansion. A technical evaluation is focused on the operational performance of 12-meter hydrogen buses. Key parameters such as energy flow characteristics, hydrogen consumption levels, and the operation of onboard systems (e.g., air conditioning) are discussed in detail. The chapter examines urban bus routes potentially suitable for hydrogen bus deployment, taking into account daily mileage, route profiles, and specific requirements related to vehicle range and refuelling infrastructure accessibility. Finally, the study outlines the anticipated environmental and economic benefits of integrating hydrogen technology into public transport systems, while identifying existing implementation challenges that must be addressed to enable broader adoption.

Keywords: hydrogen, public transport, alternative fuels, electromobility, energy transition, decarbonisation

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1. Overview

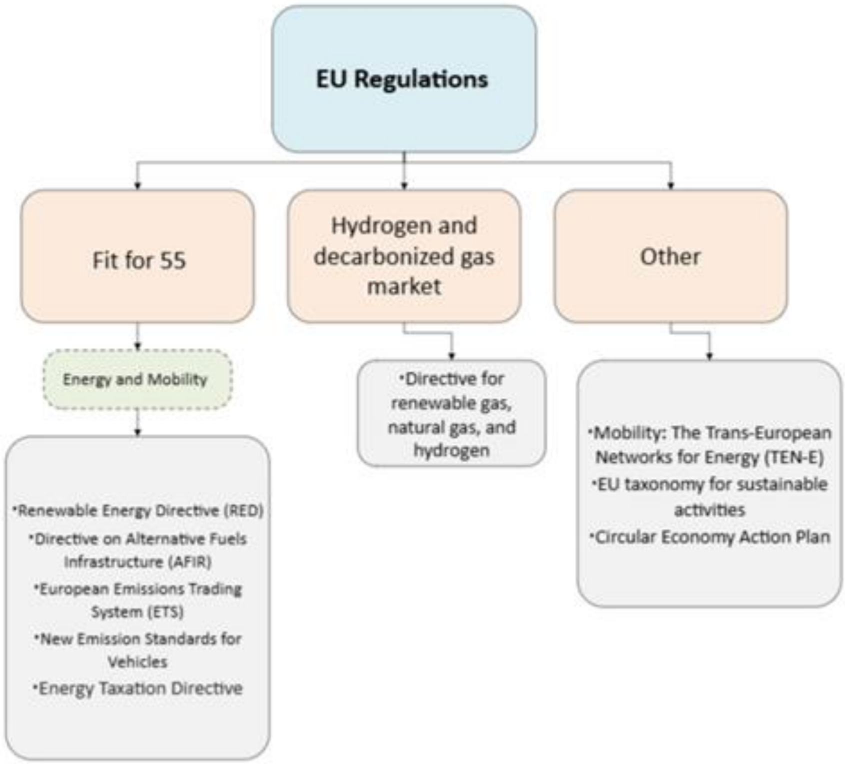
Introduction

The transformation of the transport sector towards climate neutrality requires the implementation of technological solutions based on low-emission energy sources. Road transport accounts for approximately 24% of total greenhouse gas emissions in the European Union, making it an important area of intervention in climate-energy policy [1]. In this context, hydrogen is gaining strategic importance as an alternative energy carrier with high energy density that can be used in sectors that are difficult to reduce emissions. In urban public transport, hydrogen fuel cell technology is gaining importance as a complement to electromobility (especially where infrastructure, operational or climate constraints affect the efficiency of battery-only solutions). Fuel cell based propulsion systems achieve comparable performance with shorter refuelling times, increasing their suitability for intensive urban fleets.

Legal aspects of hydrogen as an alternative fuel

According to the European Green Deal and the 2020 'European Hydrogen Strategy', hydrogen is expected to play a key role in achieving climate neutrality by the year 2050 [2,3]. The regulatory framework supporting this goal is shown in Figure 1. The 'Fit for 55' package, including the RED III Directive, AFIR, ETS and new vehicle emission standards, among others, sets ambitious targets for increasing the contribution of RES and implementing alternative fuels [4,5,6]. The RED III Directive places particular emphasis on the use of non-biological renewable fuels for transport, while the AFIR mandates the creation of a network of hydrogen refuelling infrastructure for road transport (TEN-T). In the field of the decarbonised gas market, the proposed directive on renewable gases, including hydrogen, which organises the rules for their certification and integration into the energy market, is also important. The new regulations are intended not only to stimulate investment in hydrogen technologies, but also to ensure their compliance with the principles of sustainable development. The implementation of consistent and uniform rules across the European Union is a key element that can help accelerate the commercialisation of hydrogen in the transport sector.

In Poland, the legislative framework is provided by, among others, the Act on Electromobility and Alternative Fuels and the 'Polish Hydrogen Strategy to 2030 (with a perspective to 2040)', which assumes a comprehensive development of the national hydrogen ecosystem [8]. The document identifies priority areas of state intervention in the implementation of the hydrogen economy, including the construction of a minimum of 32 publicly accessible refuelling stations and the development of associated infrastructure, the development of low-carbon footprint hydrogen production technologies (mainly by RES-powered electrolysis), the strengthening of national industrial competence and the spread of hydrogen applications in transport, energy and industry. In the area of public transport, the strategy anticipates, between others, promotion of pilot projects, deployment of hydrogen fleets in cities and development of a national production capacity for hydrogen powered vehicles. The strategy also highlights the emergence of at least 5 regional 'hydrogen valleys' - integrated ecosystems combining production, storage, distribution and end use of hydrogen to build a coherent hydrogen market on a national scale.

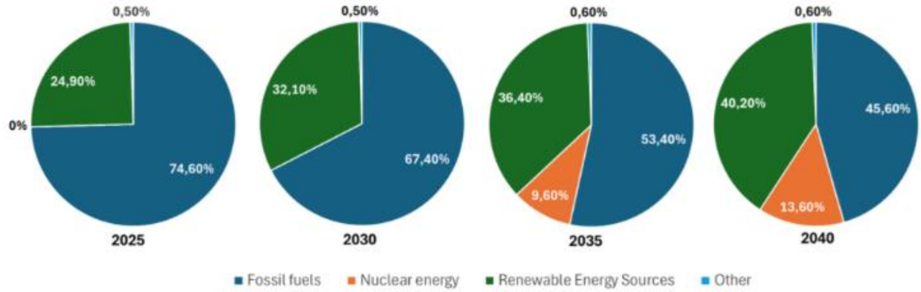


Rys. 1. Przegląd najważniejszych ram prawnych UE wspierających rozwój sektora wodorowego [7]

Fig. 1. Overview of essential EU legal frameworks supporting hydrogen sector development [7]

Role of Polish energy mix in shaping the hydrogen economy

An important factor influencing the profitability and environmental effectiveness of implementing hydrogen in transport is the energy mix. According to the 'Energy Policy of Poland until 2040', a significant reduction in the share of fossil fuels in electricity generation is intended (from about 75% in 2025 to 45% in 2040) and an increase in the share of renewable energy sources to about 40% as it is presented in the Figure 2 [6]. Complementary to this will be the development of nuclear power (to 13.6% in 2040), which will enable the production of hydrogen by electrolysis using low and zero emission energy.



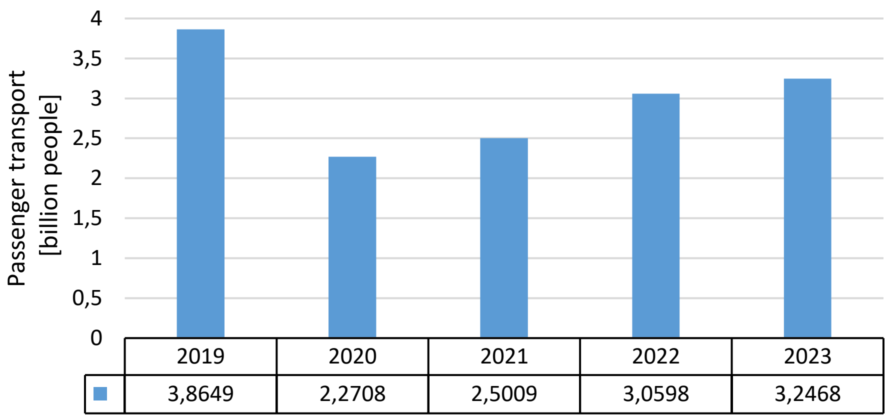
Rys. 2. Prognoza produkcji energii elektrycznej według udziału nośników energii w Polsce do 2040 roku [9]

Fig. 2. Forecast of electricity generation by energy carrier share in Poland until 2040 [9]

The projected transformation of the electricity system creates the conditions for the development of electrolysis-based hydrogen production using energy from low and zero emission sources. Green hydrogen - produced using renewable energy sources - enables significant reductions in emissions throughout the fuel's life cycle, which is necessary to meet sustainability criteria. In addition, the development of renewable energy increases the likelihood of periodic production surpluses, which can be effectively used to produce hydrogen as part of system flexibility services. The integration of electrolysers with RES and the implementation of local models (e.g. the installation of PV panels on commuter depots) also promote the energy autonomy of transport operators and the minimisation of transmission losses. The development of fuel cell technology, the relevant regulatory framework and the increasing availability of renewable energy create favourable conditions for the deployment of hydrogen-based fleet projects - especially in urban environments where there is a need to reduce local emissions and noise while maintaining high availability of public transport services. In the medium to long term perspective, hydrogen has potential to become a stable and efficient component of low-carbon urban mobility, provided that measures integrating the energy, transport and urban planning sectors are continued.

2. Analysis of Polish urban bus transport

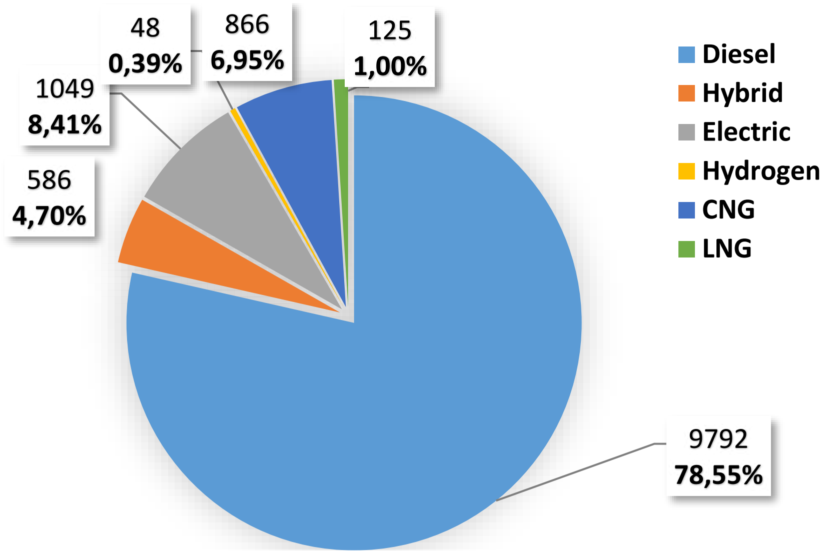
The increasing concentration of population or the increase in the number of road vehicles in urban areas results in increased air pollution, which has a negative impact on the lives and health of residents. The main source of urban air pollution is transportation. It is responsible for almost 25% of Europe's greenhouse gas emissions. Consequently, urban public transport, especially bus transport, is an important area for the implementation and development of electromobility [10,11]. The Polish bus transport market is conditioned by programs and regulations - both international and domestic as it is described in the chapter 1. According to the statistics, the number of buses used in public transportation in Poland in 2023 was 12,466 units (up by 195 since 2022). This accounted for 79.2% of the total urban transportation fleet (0.4% more than in the previous year). The total length of bus lines in Poland was 56,483.3 kilometres (up 1.8% since 2022), and the mileage of the bus transport fleet in 2023 was equal to 698.9 million vehicle kilometres (accounting for 82.3% mileage of all urban transport). Public transportation services were used by 3.2468 billion passengers (an increase of 6.1% over the previous year). Despite the upward trend in passenger transportation, bus transportation has not recovered to pre-pandemic levels yet, as it is illustrated in the Figure 3 [12].



Rys. 3. Pasażerowie polskiego transportu autobusowego w latach 2019-2023 [12]

Fig. 3. Passengers of Polish bus transportation in 2019-2023 [12]

The average daily mileage per bus was 192 km (the highest in the Świętokrzyskie Province - 214 km, and the lowest in the Warmian-Masurian Province - 136 km). Meanwhile, the average annual mileage in 2023 was 70,161 km. About 11,800 buses were adapted to the needs of people with disabilities, and their share in the total number of buses increased from 94.8% in 2022 to 95.0% in 2023. [12, 13]. Figure 4 shows the share of buses by propulsion type/power source in Polish urban bus fleet (as of December 31, 2023). Diesel buses accounted for the largest share, with 9792 units, while hydrogen buses accounted for only 0.39% of the total fleet, with 48 units [12]. Compared to previous years, a significant increase in low emission vehicles number can be observed, according to statistical data as of December 31, 2017, cities in Poland used 12,118 buses, of which 502 were low emission buses (4.1% of the total number of buses). In 2023, their share has grew to 21.45% of the total bus fleet [12,14]. These figures are summarized in Table 1.



Rys. 4. Udział autobusów według paliwa w polskiej flocie autobusów miejskich (stan na 31 grudnia 2023 r.) [12]

Fig. 4. Share of buses by fuel in Polish urban bus fleet (as of December 31, 2023) [12]

Tabela 1. Udział autobusów niskoemisyjnych w całkowitej flocie autobusowej w 2017 i 2023 r. [12,14]

Table 1. Share of low emission buses in the total bus fleet in 2017 and 2023 [12,14]

Year	Total number of buses	Number of low emission buses	Percentage of low emission buses in the total fleet [%]
2023	12 466	2 674	21,45
2017	12 118	512	4,1

3. Refuelling infrastructure

Currently in Poland, there are only a few hydrogen filling stations available located in the largest cities, most of which are open to the public (see Table 2). According to the assumptions of the ‘Polish Hydrogen Strategy to 2030 with an Outlook to 2040’, the number of hydrogen filling stations should increase to 32 units [8]. The strategy also involves the development of two additional hydrogen production hubs. The first hydrogen refuelling station was established in 2022 for the Kraków municipal transport company [15].

Tabela 2. Stacje tankowania wodoru w Polsce [15,16,17,18]

Table 2. Hydrogen fuelling stations in Poland [15,16,17,18]

Publicly accessible stations		
Location	**Owner**	**EIPA no.**
Warszawa ul. Tango 4	PAK-PCE Stacje H2 Sp. z o.o.	PL-A54-P00000104
Rybnik ul. Budowlanych 6	PAK-PCE Stacje H2 Sp. z o.o.	PL-A54-P00000136
Gdańsk ul. Jabłoniowa	PAK-PCE Stacje H2 Sp. z o.o.	PL-A54-P00000140
Gdynia ul. Starochwaszczyńska	PAK-PCE Stacje H2 Sp. z o.o.	PL-A54-P00000139
Wrocław ul. Obornicka 187	PAK-PCE Stacje H2 Sp. z o.o.	PL-A54-P00000135
Lublin ul. E. Plewińskiego	PAK-PCE Stacje H2 Sp. z o.o.	PL-A54-P00000153
Katowice ul. Murckowska 22	ORLEN S.A.	PL-PKN-P04280000
Poznań ul. Warszawska 231	ORLEN S.A.	PL-PKN-P13280000
Non-commercial stations		
Location	**Owner**	**Description**
Kraków	ORLEN S.A.	Mobile refuelling station
Konin	ZE PAK	Mobile refuelling station
Solec Kujawski	SOLBET	For the needs of company (forklifts and passenger cars)
Wałbrzych	ORLEN S.A.	Mobile refuelling station

The use of publicly available hydrogen refuelling stations is essentially no different from the operation of traditional petrol stations, and no additional authorisation is required to use it. The refuelling process takes a few to several minutes, depending on the capacity of the tank and the pressure standard. The filling speed, which in the case of the H35 standard is limited to 120g/s, is defined by the SAE J2601 refuelling protocol. It contains detailed information on the permissible parameters during refuelling (including temperature, pressure, method of communication with the vehicle, station performance category). The data are collected in a tabular form of a so-called lookup table specifying the target refuelling pressure. The second acceptable method is the MC formula based on a regression equation determining the time required for refuelling by controlling the pressure increment.

Rys. 5. Mobilna stacja tankowania wodoru

Fig. 5. Mobile hydrogen refuelling station

The common pressure standard for hydrogen buses is H35, which means a tank filling pressure of 350 bar. In the case of mobile hydrogen refuelling stations (see Figure 5) not equipped with an additional compression system, this pressure is limited to approximately 200 bar, which results in incomplete filling of the tanks with hydrogen and a consequent decrease in vehicle total range.

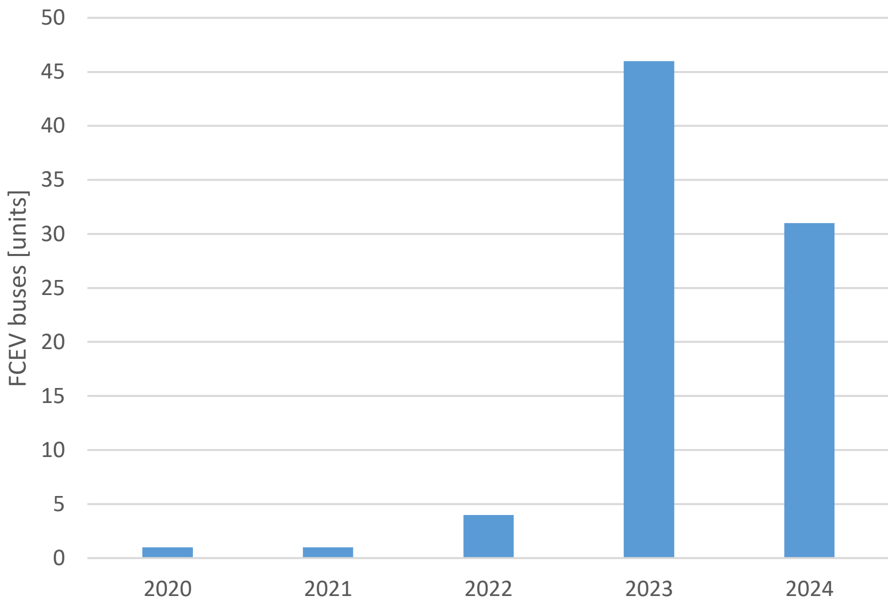
4. Polish hydrogen bus market

The first hydrogen powered vehicle was registered in Poland in 2017, but the registration of the first hydrogen bus happened in 2020. In the following years, a gradual increase in their registration could be seen (see Table 3), the reasons for which are regarded as the development of refuelling infrastructure and increasingly stringent requirements for city bus fleets. The current number of all FCEV buses in Poland is estimated at around 90 units. Due to the amendment of the law on electromobility [19], further growth of interest in this technology is expected among public transport fleet operators in cities with more than 100,000 citizens.

To get a better idea of the size of Polish hydrogen bus market, it is worth to look at Japan as a leader in the implementation of this type of solution in urban public transport. The first FCEV bus appeared in regular use on a route in Tokyo in 2018, while by early 2023 there were already 124 buses in use. The Japanese government forecast assumes introduction of 1200 buses by 2030, which will be combined with the expansion of refuelling infrastructure to up to 1000 stations [22,23].

Tabela 3. Rejestracje autobusów wodorowych w Polsce w latach 2020-2024 [20,21]

Table 3. Hydrogen buses registrations in Poland 2020-2024 [20,21]



The most numerous group among city buses are so called MAXI class buses. They are characterised by a length of 11 to 13 metres and a total number of seats of about 90. They seems to be ideally suited to serve busy urban and suburban routes mainly due to the compromise between compact size, manoeuvrability and relatively large capacity. Currently, in the offer of manufacturers on the Polish market, we can find 5 models of hydrogen buses classified as MAXI, whose selected parameters are compared in Table 4.

Of the buses presented in the table above, the Mercedes-Benz stands out significantly with the greatest range declared. Such difference is related to its different design, as it is the only bus in comparison in which the fuel cell acting as a range extender and is not the main source of propulsion, which in this case is a traction battery with a much higher capacity than its competitors. Such solution increases the total weight of the vehicle, however in addition to increasing the effective range, it also allows for more stable operating conditions for the fuel cell, which in turn can result in a longer lifespan. At this point, it is also worth mentioning that the NesoBus and ArthurBus are vehicles designed as FCEVs from scratch and, unlike the others, are not based on previously developed BEV models

Tabela 4. Porównanie 12-metrowych autobusów FCEV dostępnych na polskim rynku [24,25,26,27,28]

Table 4. Comparison of 12m FCEV buses available on Polish market [24,25,26,27,28]

Model		NesoBus 12	Solaris Urbino 12 Hydrogen	Mercedes-Benz eCitaro fuel cell	Arthur Bus H2 Zero	Autosan Sancity 12LFH
Fuel cell power [kW]		70	70	60	70	70
Lenght [mm]		12 000	12 000	12 135	12 015	12 000
Gross mass [kg]		19 500	19 200	20 000	no data	no data
Hydrogen tanks	Capacity [kg]	37,5	37,5	25	37,5	31
	Pressure [bar]	350/700*	350	350	350	350
Battery [kWh]		30,4 (LTO)	30,47 (Li-ion)	294 (NMC3)	no data	45 (LTO)
Max power [kW]		2 x 125	2 x 125	250	2 x 125	253
Max range [km]		450	350	600	350	400

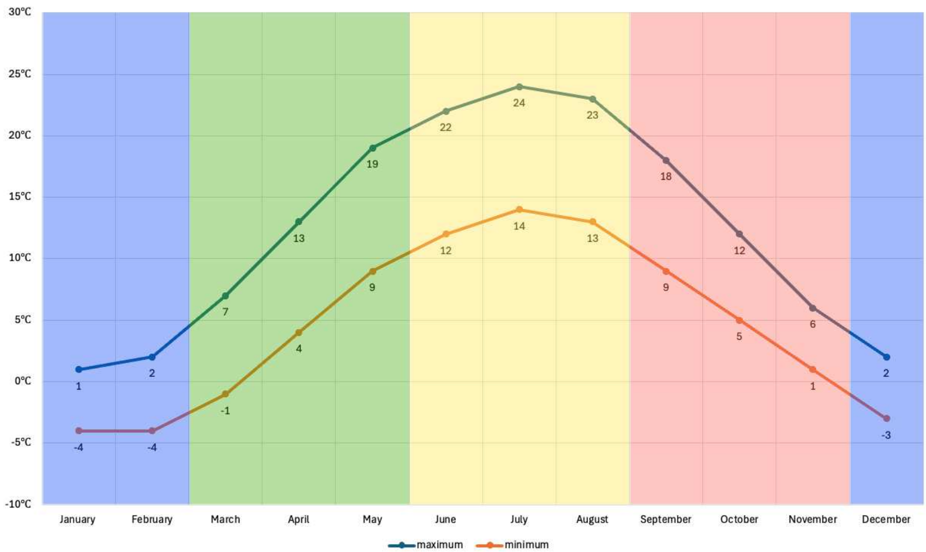
* - *optional*

Of the buses presented in the table above, the Mercedes-Benz stands out significantly with the greatest range declared. Such difference is related to its different design, as it is the only bus in comparison in which the fuel cell acting as a range extender and is not the main source of propulsion, which in this case is a traction battery with a much higher capacity than its competitors. Such solution increases the total weight of the vehicle, however in addition to increasing the effective range, it also allows for more stable operating conditions for the fuel cell, which in turn can result in a longer lifespan. At this point, it is also worth mentioning that the NesoBus and ArthurBus are vehicles designed as FCEVs from scratch and, unlike the others, are not based on previously developed BEV models.

5. Energy consumption analysis

The following section is dedicated to daily energy consumption analysis of 12m MAXI bus with four types of propulsion source: CNG, Diesel, electric and hydrogen in relation to seasonal variations of temperature in Poland. Information regarding to daily energy consumption of air conditioning, heating and on-board equipment were taken into consideration and broken down into four operating periods corresponding with seasons.

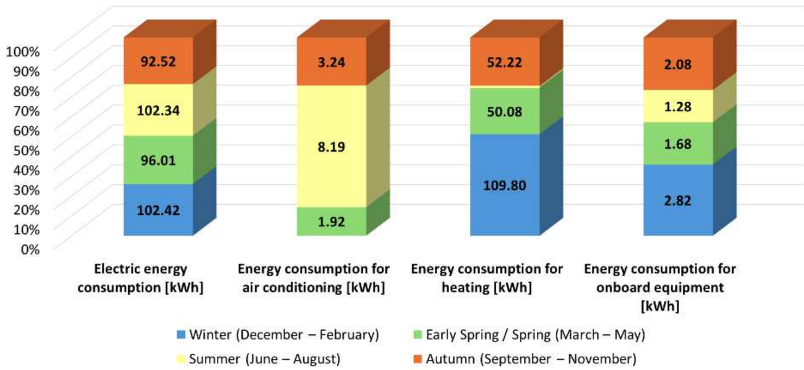
The climatic diversity of Poland has a direct impact on the profile of vehicle energy consumption, mainly due to the transient nature of the climate and thus the high variability of the weather conditions. As it is presented on the graph (see Figure 6) the average monthly maximum and minimum temperatures in Poland. range from -4°C (January-February) up to 24°C (July). Consequently the winter months require intense heating of a bus, while during summer months (June-August) demand for cooling increases.



Rys. 6. Średnie maksymalne i minimalne temperatury miesięczne w Polsce w określonych okresach roboczych [29]

Fig. 6. Average max. and min. monthly temperatures in Poland over specified operating periods [29]

Figure 7 depicts the seasonal energy consumption of the electric bus. It is noticeable the relatively low electricity consumption for air conditioning (maximum 8,19 kWh in the summer period) and on-board equipment (maximum 2,82 kWh in winter period). Despite the high contribution of heating to the overall energy demand in winter (109,80 kWh), this energy does not come from batteries, but it is sourced from an independent diesel powered auxiliary heating system often offered in vehicles destined for the Scandinavian markets.

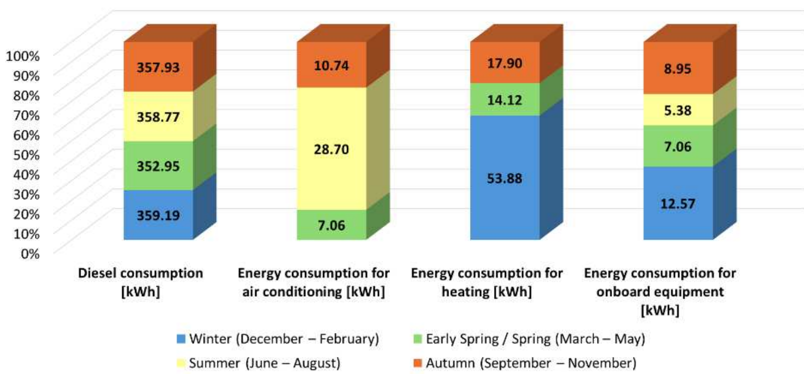


Rys. 7. Sezonowe dzienne zużycie energii przez 12-metrowy autobus elektryczny

Fig. 7. Seasonal daily energy consumption of 12m electric bus

The electric bus has relatively low electricity consumption for all onboard systems during both summer and winter. Thanks to the application of auxilary heating system, a significant load on the battery system is avoided in winter, which has a positive impact on the vehicle operational range in low temperature. Such solution minimises the impact of seasonality on operating efficiency, although it involves partial harmful emissions resulting from combustion of diesel fuel.

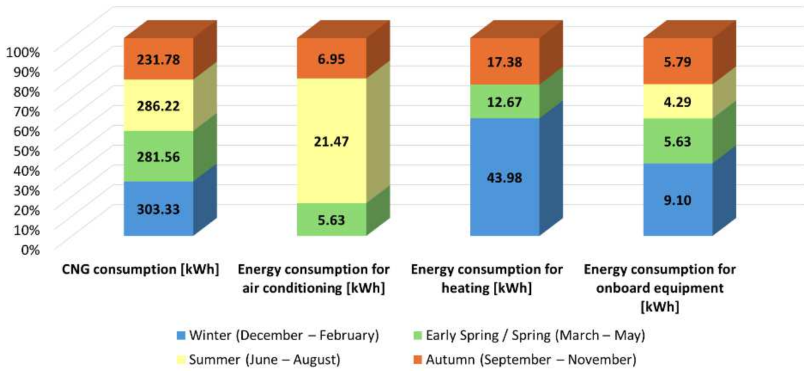
Energy consumption of a conventional Euro VI diesel bus is illustrated in the Figure 8. The amount of energy derived from fuel remains almost constant throughout the year and is approximately 357 kWh for each season. The highest energy consumption is observed for heating system operation during winter (53,88 kWh) and for air conditioning in summer period (28,70 kWh).



Rys. 8. Sezonowe dzienne zużycie energii przez 12-metrowy autobus z silnikiem wysokoprężnym

Fig. 8. Seasonal daily energy consumption of 12m diesel bus

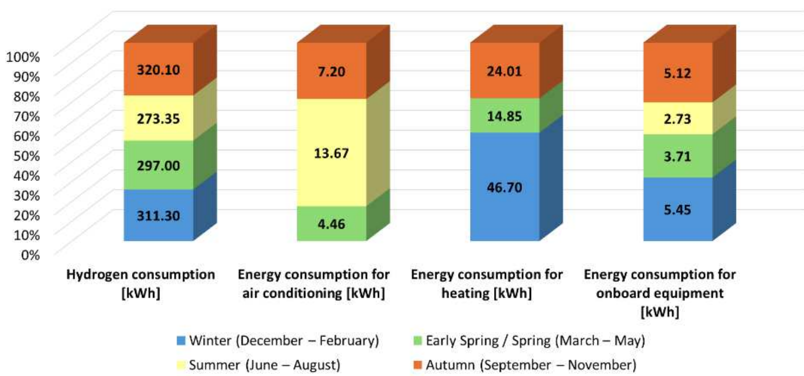
The total diesel bus energy demand is stable regardless of the season. Energy consumption is higher compared to other bus types, however this ensures precise prediction of its operation in any external conditions.



Rys. 9. Sezonowe dzienne zużycie energii przez 12-metrowy autobus CNG

Fig. 9. Seasonal daily energy consumption of 12m CNG bus

Another case under consideration was a bus powered by compressed natural gas. As can be seen in the Figure 9, the highest energy consumption for heating occurs in winter (43,98 kWh), while in summer a noticeable increase in energy consumption for air conditioning occurs (21,47 kWh). A CNG powered bus presents significant seasonal variation in energy consumption, with the highest demand occurring both in winter and summer. During autumn total energy consumption drops to its lowest values (231,78 kWh), which translate directly to the bus top operational efficiency.



Rys. 10. Sezonowe dzienne zużycie energii przez 12-metrową magistralę wodorową

Fig. 10. Seasonal daily energy consumption of 12m hydrogen bus

The last of the cases considered was a hydrogen powered bus. As the seasonal energy profile for the hydrogen bus shows (see Figure 10), energy demand is less evenly distributed throughout the year than in case of CNG bus. A slight increase in heating demand in winter (46,70 kWh) and moderate consumption for air conditioning system in summer (13,67 kWh) was observed.

6. Summary

Considering the projected expansion of the energy system in the upcoming years, based on an increase in the share of renewable sources and the legal conditions, it seems reasonable to carry out research aimed at the use of low emission propulsion systems in public transport vehicles. The noticeable increase in interest in hydrogen vehicles is reflected in the growing number of registrations and the expansion of refuelling station infrastructure, which suggests that this trend will continue for the next few years.

Conducted analysis of the Polish urban bus transport market shows that public transport has a share of over 80%. A significant increase in the share of alternatively powered buses relative to the total fleet is also observed, with hydrogen buses playing an increasingly important role in the fleet.

The study showed significant differences in the seasonal energy consumption of buses with different propulsion systems:

- electric bus has the lowest electricity consumption regardless of the season. Thanks to the use of an independent heating system (powered by diesel), excessive load on the batteries is avoided in winter. This solution maintains high operating efficiency even at low temperatures, although it introduces an element of exhaust emissions in addition to the main drive;
- diesel bus exhibits the most stable energy consumption profile over the year. Its independence from weather conditions makes it a predictable solution, however one that generates higher emissions, which is at variance with the European Union development strategy;
- hydrogen bus offers a balanced energy consumption profile and good adaptation to varying climatic conditions. It can provide compromise between efficiency and low emissions, but it requires further infrastructure development;
- CNG powered bus presents a noticeable decrease in available energy during the autumn season, which can limit its operability. Energy consumption is seasonally variable, particularly in winter and summer periods.

In the context of the move towards zero-emission public transport, electric and hydrogen buses are currently the most promising technologies. The choice of the optimal solution should take into account not only emissions, but also local climate conditions, infrastructure and operational strategy, including the use of auxiliary energy sources such as supplementary heating systems in electric buses.

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OCENA EFEKTYWNOŚCI I DZIAŁANIA 12-METROWEGO AUTOBUSU MIEJSKIEGO O NAPĘDZIE WODOROWYM W POLSKICH WARUNKACH EKSPLOATACYJNYCH

Streszczenie

Rozdział przedstawia analizę kluczowych aspektów związanych z wprowadzeniem wodoru jako paliwa w miejskim transporcie publicznym w Polsce. Omówiono zagadnienia prawne dotyczące produkcji jak i wykorzystania wodoru w transporcie drogowym, z uwzględnieniem obowiązujących regulacji krajowych oraz przepisów prawa unijnego, które wspierają rozwój technologii wodorowych jako elementu strategii dekarbonizacji transportu. W pracy podkreślono znaczenie odpowiedniego otoczenia legislacyjnego jako warunku koniecznego dla wdrażania paliw alternatywnych, w tym wodoru, w sektorze transportu publicznego. Opracowanie zawiera również szczegółową analizę krajowego rynku energetycznego w kontekście możliwości produkcji wodoru, ze wskazaniem na jego rosnące znaczenie w powiązaniu z odnawialnymi źródłami energii oraz transformacją całego sektora transportowego w kierunku zeroemisyjności. Analizie poddano rozwój krajowego rynku pojazdów wodorowych, koncentrując się na autobusach miejskich, przy uwzględnieniu liczby rejestrowanych pojazdów na przestrzeni lat, dostępnych na rynku modeli oraz tempa rozwoju infrastruktury niezbędnej do tankowania wodoru. W rozdziale omówiono również istotne aspekty techniczne związane z funkcjonowaniem 12-metrowych autobusów wodorowych, w tym charakterystykę przepływu energii, poziomy zużycia paliwa oraz sposób zasilania urządzeń pokładowych, takich jak systemy klimatyzacji, ogrzewania czy układy wspomagania. W kontekście eksploatacyjnym przeprowadzono analizę tras miejskich, na których mogą być wykorzystywane autobusy wodorowe, uwzględniając m.in. dzienne przebiegi, profile operacyjne tras oraz specyficzne wymagania dotyczące zasięgu pojazdu i dostępności infrastruktury tankowania. rozdział podkreśla potencjalne korzyści wynikające z wdrożenia technologii wodorowej w transporcie publicznym, zarówno w ujęciu ekologicznym, jak i ekonomicznym, jednocześnie wskazując na istniejące bariery wdrożeniowe.

Słowa kluczowe: wodór, transport publiczny, paliwa alternatywne, elektromobilność, transformacja energetyczna, dekarbonizacja

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WPŁYW MIĘDZYNARODOWYCH REGULACJI EMISYJNYCH NA WYBÓR PALIW BEZEMISYJNYCH W ŻEGLUDZE

W rozdziale przeanalizowano wpływ międzynarodowych i regionalnych regulacji emisyjnych, takich jak MARPOL Annex VI, strategia IMO GHG, FuelEU Maritime i system EU ETS, na wybory paliw alternatywnych w żegludze morskiej. Celem pracy było wskazanie, w jaki sposób normy prawne wpływają na decyzje inwestycyjne armatorów dotyczące napędów bezemisyjnych. W badaniach zastosowano autorski metamodel decyzyjny integrujący aspekty techniczne, środowiskowe, ekonomiczne i prawne. Model ten uwzględniał parametry eksploatacyjne statków, ocenę cyklu życia paliw (LCA), zgodność z wskaźnikami EEDI, EEXI i CII oraz analizę wielokryterialną (MCDA) opartą na metodzie AHP. Wyniki wskazują, że wodór i amoniak mają największy potencjał w długoterminowym spełnianiu wymogów regulacyjnych, o ile zapewnione zostanie wsparcie infrastrukturalne i polityczne. LNG i metanol pozostają natomiast konkurencyjnymi opcjami przejściowymi, zwłaszcza w żegludze regionalnej. Analiza potwierdza, że wybór paliwa musi wynikać nie tylko z kryteriów kosztowych, ale również z konieczności zgodności z zaostrzającymi się normami emisyjnymi. Opracowany model może być narzędziem wspomagającym strategiczne decyzje inwestycyjne w sektorze morskim, wspierając proces dekarbonizacji floty w perspektywie 2030–2050.

Słowa kluczowe: MCDA, LCA, wodór, amoniak, lng, metanol

1. Wstęp

Postępujące zmiany klimatyczne, rosnąca świadomość ekologiczna społeczeństw oraz intensyfikacja międzynarodowych działań na rzecz zrównoważonego rozwoju stawiają przed sektorem żeglugi morskiej poważne wyzwania. Transport morski odpowiada za około 2,5–3% globalnych emisji gazów cieplarnianych, a jego udział może wzrosnąć w nadchodzących dekadach, jeśli nie zostaną wdrożone odpowiednie środki ograniczające emisje [1][2]. Presja ze strony instytucji międzynarodowych, konsumentów, partnerów handlowych oraz inwestorów powoduje, że coraz więcej armatorów i operatorów flot musi dostosowywać swoje strategie do zaostrzających się norm środowiskowych [3].

W tym kontekście kluczową rolę odgrywa Międzynarodowa Organizacja Morska (IMO), która wprowadza globalne przepisy mające na celu redukcję emisji zanieczyszczeń powietrza ze statków.

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MARPOL Annex VI oraz strategia redukcji gazów cieplarnianych IMO wyznaczają kierunki dla dekarbonizacji sektora [4][5]. Jednocześnie Unia Europejska wprowadza niezależne, a często jeszcze bardziej rygorystyczne regulacje, takie jak pakiet Fit for 55 czy FuelEU Maritime, które obejmują również statki pływające w obrębie i do/z portów europejskich [6][7].

Równolegle do rozwoju regulacji prawnych postępuje rozwój technologii napędowych i paliw alternatywnych. Wybór odpowiedniego paliwa staje się decyzją wielowymiarową – musi uwzględniać nie tylko koszty i dostępność infrastruktury, ale przede wszystkim zgodność z aktualnymi i prognozowanymi wymogami prawnymi oraz wpływ środowiskowy [8][9].

2. Ramy regulacyjne – IMO i UE

MARPOL Annex VI

MARPOL Annex VI ustanawia globalne limity emisji SO_x, NO_x i CO_2, które mają bezpośredni wpływ na rodzaje używanych paliw. Od 2020 r. obowiązuje globalny limit zawartości siarki w paliwie na poziomie 0,50%, co wyeliminowało możliwość stosowania tradycyjnych paliw ciężkich bez odpowiedniego oczyszczania gazów spalinowych [10]. W ramach tego aneksu wprowadzono również wskaźniki efektywności energetycznej, takie jak EEDI (dla nowych jednostek) oraz EEXI (dla istniejących), a także operacyjne wskaźniki intensywności emisji, takie jak CII [11][12].

Wskaźniki te mają na celu skłonienie armatorów do modernizacji jednostek, wyboru bardziej efektywnych technologii oraz stosowania paliw niskoemisyjnych. Spełnienie norm MARPOL staje się istotnym kryterium decyzyjnym przy projektowaniu nowych statków i przy inwestycjach flotowych [13].

Strategia IMO GHG

Początkowa strategia IMO dotycząca redukcji emisji gazów cieplarnianych, przyjęta w 2018 r. (rezolucja MEPC.304(72)), zakłada redukcję intensywności emisji CO_2 o 40% do 2030 r. oraz redukcję całkowitych emisji GHG o 50% do 2050 r. względem poziomów z 2008 r. [14]. W 2023 r. przyjęto rewizję tej strategii, podnosząc cele: 20% redukcji do 2030 r., 70% do 2040 r. oraz pełną dekarbonizację około 2050 r. [15].

Realizacja tych celów wymaga nie tylko usprawnień technicznych i operacyjnych, ale przede wszystkim stopniowego przechodzenia na paliwa alternatywne. W szczególności, IMO dąży do tego, aby co najmniej 5% (a docelowo 10%) energii wykorzystywanej przez statki do 2030 r. pochodziło z paliw o zerowej lub niemal zerowej emisji gazów cieplarnianych [15].

Polityka klimatyczna UE

Równolegle do działań IMO, Unia Europejska wdraża własne środki w ramach pakietu Fit for 55. Jednym z kluczowych rozwiązań jest włączenie żeglugi morskiej do unijnego systemu handlu emisjami (EU ETS), co oznacza konieczność zakupu uprawnień do emisji CO_2 przez operatorów statków zawijających do portów UE [16]. Obejmuje to 100% emisji z rejsów wewnątrz UE oraz 50% z rejsów przychodzących i wychodzących spoza UE [16].

Kolejnym filarem unijnej polityki morskiej jest rozporządzenie FuelEU Maritime, które ustala maksymalną dopuszczalną intensywność emisji GHG w zużywanej energii (well-to-wake). Od 2025 r. intensywność ta będzie sukcesywnie obniżana: 2% w 2025 r., 6% w 2030 r., aż do 80% w 2050 r. [17]. Wymusza to przejście na paliwa odnawialne lub syntetyczne oraz rozwój infrastruktury dla ich bunkrowania. Uzupełnieniem jest rozporządzenie AFIR, zobowiązujące państwa członkowskie do rozbudowy infrastruktury dla paliw alternatywnych, w tym LNG, wodoru i amoniaku [18].

Unijne regulacje – przez bodźce ekonomiczne (ETS), normy jakości paliw (FuelEU) i wymogi infrastrukturalne (AFIR) – kreują warunki rynkowe, które premiują stosowanie paliw alternatywnych i stopniowo eliminują paliwa wysokoemisyjne z eksploatacji [19]. Znaczenie wskaźników EEDI, EEXI i CII

3. Znaczenie wskaźników EEDI, EEXI i CII

EEDI (Energy Efficiency Design Index)

EEDI dotyczy nowych jednostek i określa minimalne wymagania dotyczące efektywności energetycznej statku już na etapie projektowania. Wskaźnik obliczany jest jako stosunek emisji CO_2 do przewożonego ładunku i przebytej odległości (gCO_2/tonomila). Jest on obowiązkowy od 2013 r. dla większości typów nowych statków powyżej 400 GT i podlega etapowej redukcji, co wymusza projektowanie coraz bardziej efektywnych jednostek [20]. W fazie 3 (od 2022 r.) niektóre typy statków muszą zredukować emisje nawet o 30% względem poziomu referencyjnego z 2008 r. [21].

EEDI zachęca projektantów i armatorów do inwestycji w nowoczesne konstrukcje kadłubów, energooszczędne śruby napędowe, nowoczesne silniki o niższym zużyciu paliwa, a także alternatywne systemy napędowe – w tym zasilanie LNG, metanolem czy wodorem [22].

EEXI (Energy Efficiency Existing Ship Index)

EEXI został wprowadzony w 2023 r. jako odpowiednik EEDI dla istniejących jednostek. Ocenia efektywność energetyczną jednostki względem referencyjnego poziomu emisji dla danego typu statku i rocznika. Wymaga od operatorów przeprowadzenia oceny oraz – w przypadku niespełnienia norm – wdrożenia środków naprawczych [23].

Najczęstsze metody poprawy EEXI to: zastosowanie systemu ograniczania mocy silnika (Engine Power Limitation, EPL), modernizacja układów napędowych, poprawa opływowości kadłuba lub przejście na paliwo o niższej emisyjności, np. LNG [24]. Dla wielu starszych statków EEXI stał się impulsem do decyzji o modernizacji lub wycofaniu jednostek z eksploatacji, co ma pozytywny wpływ na redukcję emisji w sektorze [25].

CII (Carbon Intensity Indicator)

CII mierzy intensywność emisji CO_2 podczas eksploatacji jednostki (gCO_2/dwt-mile) i dotyczy wszystkich statków powyżej 5000 GT. Każda jednostka otrzymuje roczną ocenę w skali od A (najlepsza) do E (najgorsza). Wymagane poziomy CII są stopniowo zaostrzane, a jednostki ocenione na D lub E przez trzy kolejne lata muszą wdrożyć plan korekcyjny [26].

Wskaźnik CII uwzględnia rzeczywiste dane z eksploatacji, co czyni go narzędziem dynamicznym i pozwalającym na bieżąco monitorować efektywność energetyczną floty. Armatorzy są zmuszeni do optymalizacji tras, zarządzania prędkością, a także inwestycji w paliwa niskoemisyjne, aby poprawić ocenę CII [27].

Dla środowiska naturalnego wdrożenie CII oznacza systematyczne ograniczanie emisji gazów cieplarnianych w oparciu o realne dane operacyjne, natomiast dla armatorów stanowi silną motywację do stosowania innowacyjnych rozwiązań technologicznych i organizacyjnych w celu utrzymania konkurencyjności [28].

4. Metamodel badawczy – integracja aspektów prawnych z technicznymi

W celu przeprowadzenia kompleksowej analizy wyboru paliwa w żegludze morskiej, opracowano metamodel decyzyjny, który integruje dane techniczne, środowiskowe, ekonomiczne i prawne. Jego struktura pozwala na wieloaspektową ocenę scenariuszy operacyjnych, uwzględniając obowiązujące oraz prognozowane regulacje międzynarodowe (IMO) i unijne (UE) [29][30].

Model oparty jest na siedmiu komponentach:

1) Parametry statku – podstawowe dane techniczne jednostki, takie jak tonaż, moc silnika, typ napędu, rok budowy, profil trasy i średnia prędkość. Pozwala to określić wymagania energetyczne i oszacować emisje w zależności od wybranego paliwa [31].
2) Model mezoskalowy ruchu statku – symulacja operacyjnych warunków eksploatacji jednostki (opracowany w Simulinku). Umożliwia realistyczne odwzorowanie wpływu prędkości, dystansu, ładowności i warunków pogodowych na zużycie paliwa oraz emisje [32].
3) Charakterystyka paliwa – dane fizykochemiczne paliw alternatywnych (LNG, metanol, amoniak, wodór) obejmujące gęstość energetyczną, właściwości

spalania, emisje punktowe oraz zapotrzebowanie na infrastrukturę bunkrową [33].

4) Ocena cyklu życia (Life Cycle Assessment, LCA) – analiza śladu węglowego i emisji zanieczyszczeń w całym cyklu życia paliwa (well-to-wake), z uwzględnieniem sposobu produkcji, transportu, magazynowania i zużycia [34]. Pozwala porównać realny wpływ różnych paliw na środowisko, a nie tylko ich emisje pokładowe.
5) Model statystyczny emisji – predykcja emisji CO_2, NO_x, SO_x i CH_4 na podstawie danych historycznych, katalogów floty oraz przewidywanych scenariuszy użytkowania statków [35]. Model korzysta z danych AIS oraz baz danych technicznych (np. SeaWeb, IMO GISIS).
6) Zgodność z przepisami – ocena poziomu zgodności statku i danego paliwa z aktualnymi oraz przyszłymi wymaganiami EEDI, EEXI, CII, FuelEU Maritime i EU ETS. Model przypisuje wagi penalizacyjne dla rozwiązań niezgodnych z obowiązującymi normami [36].
7) Analiza MCDA (Multi-Criteria Decision Analysis) – moduł oceniający scenariusze paliwowe w oparciu o cztery kryteria: efektywność energetyczna, koszt całkowity (CAPEX + OPEX), zgodność z regulacjami oraz wpływ środowiskowy w cyklu życia. Analiza oparta jest na metodzie AHP (Analytic Hierarchy Process) i uwzględnia różne wagi w zależności od typu statku i operatora [37].

Metamodel został zaimplementowany przy użyciu narzędzi MATLAB/Simulink (część dynamiczna), Python (symulacje porównawcze), Excel VBA (kalkulacje kosztów) oraz baz danych SQL. Końcowym wynikiem metamodelu jest rekomendacja optymalnego paliwa dla danego profilu statku, trasy oraz przewidywanego horyzontu czasowego (krótko-, średnio- lub długoterminowy) [38]. jest rekomendacja optymalnego paliwa dla danego profilu statku i regionu operacyjnego.

5. Wyniki analizy MCDA

Na podstawie zaimplementowanego modelu obliczeniowego, który uwzględniał zarówno dane techniczno-eksploatacyjne, jak i wyniki oceny cyklu życia (LCA), przeprowadzono wielokryterialną analizę porównawczą (MCDA) dla pięciu paliw: LNG, metanolu, wodoru, bio-paliw i amoniaku. W analizie przyjęto zestaw wag przypisanych poszczególnym kryteriom, zgodnie z założeniami IPB (ang. Integrated Performance-Based approach). Kryteriami były m.in. emisje CO_2, NO_x, SO_2 i pyłów zawieszonych (PM), efektywność energetyczna, koszty operacyjne i inwestycyjne, dostępność infrastruktury oraz pełen cykl życia paliwa (produkcja, dystrybucja, utylizacja) [39][40].

W wyniku analizy MCDA, po znormalizowaniu wszystkich danych oraz uwzględnieniu wag, najwyższą łączną wartość osiągnęły paliwa bezemisyjne: wodór oraz amoniak. Wodór uzyskał najwyższe oceny w zakresie emisji CO_2

i NO_x oraz efektywności energetycznej, natomiast amoniak wyróżniał się niskim śladem węglowym w całym cyklu życia oraz umiarkowanymi wymaganiami infrastrukturalnymi. Bio-paliwa i metanol uzyskały średnie wartości, natomiast LNG – mimo dobrego wyniku energetycznego – został obciążony relatywnie wyższymi emisjami metanu (methane slip) oraz CO_2 w produkcji [41].

Równolegle obliczono uproszczony wskaźnik EEXI dla każdego paliwa, bazując na wzorze: EEXI = (zużycie paliwa * współczynnik emisji CO_2) / (odległość * ładowność). Wskaźnik ten wykazał zdecydowaną przewagę paliw bezwęglowych – wodoru i amoniaku – nad LNG, metanolem i bio-paliwami, co potwierdza ich potencjał w spełnianiu długoterminowych wymagań IMO [42].

Analogicznie, obliczenia wskaźnika CII (Carbon Intensity Indicator) wykazały, że jedynie wodór i amoniak pozwalają uzyskać najniższy poziom intensywności emisji CO_2 w przeliczeniu na jednostkę ładunku i odległość transportu. Paliwa te mogą osiągnąć ocenę A lub B w klasyfikacji CII w horyzoncie 2030–2040 bez potrzeby dalszych modernizacji [43].

Dla uzupełnienia analizy wykonano również wizualizacje danych, przedstawiające wyniki MCDA, porównanie wartości EEXI i CII oraz wpływ emisji CO_2 w całym cyklu życia (produkcja, dystrybucja, utylizacja). Wskazuje to na konieczność równoczesnego uwzględniania parametrów środowiskowych, technicznych i kosztowych przy projektowaniu strategii dekarbonizacji żeglugi morskiej.

W oparciu o metamodel i analizę wielokryterialną (MCDA), przeprowadzono ocenę czterech paliw alternatywnych: wodoru, amoniaku, LNG i metanolu. Kryteriami były: efektywność energetyczna, koszt całkowity, zgodność z regulacjami (EEXI, CII) oraz wpływ środowiskowy w ujęciu LCA.

Statki dalekiego zasięgu (long-range)

W przypadku jednostek operujących na trasach międzykontynentalnych, gdzie obowiązują najbardziej rygorystyczne wymogi regulacyjne, najlepsze wyniki osiągnęły:

- Wodór – najwyższy potencjał dekarbonizacji; brak emisji CO2 w miejscu użytkowania; zgodność z przyszłymi wymaganiami prawnymi; barierą pozostaje infrastruktura.
- Amoniak – bardzo dobre wyniki środowiskowe i zgodność z regulacjami; wyzwania związane z toksycznością i emisjami NOx mogą być zredukowane poprzez technologie oczyszczania spalin.

Oba paliwa wymagają wysokich nakładów inwestycyjnych, jednak są najkorzystniejsze w perspektywie 10–20 lat pod względem zgodności z politykami IMO i UE oraz kosztów cyklu życia.

Statki krótkiego zasięgu (short-sea)

Dla jednostek operujących na trasach lokalnych i regionalnych bardziej opłacalne są:

- LNG – paliwo przejściowe, dostępne bunkrowanie, niższe emisje CO2 w porównaniu z HFO, ale problem metanowego "slipu".
- Metanol – łatwy w transporcie i magazynowaniu, kompatybilność z istniejącą infrastrukturą, korzystny koszt inwestycyjny.

W analizie MCDA LNG i metanol osiągnęły wysokie oceny w kryteriach ekonomicznych i technicznych, szczególnie w scenariuszach krótkoterminowych (do 2035 roku).

6. Wnioski i rekomendacje

Analiza przeprowadzona w oparciu o metamodel decyzyjny oraz wielokryterialną ocenę MCDA wykazała, że międzynarodowe i unijne regulacje emisyjne stanowią główny czynnik determinujący zmiany technologiczne w sektorze żeglugi. W szczególności, normy takie jak MARPOL Annex VI, EEXI i CII oraz strategia IMO GHG wywierają presję na armatorów, aby stopniowo wycofywać paliwa wysokoemisyjne i wdrażać rozwiązania zgodne z celami dekarbonizacji. Zgodność z regulacjami prawnymi staje się obecnie równie istotna jak koszty operacyjne i inwestycyjne, co znajduje odzwierciedlenie w decyzjach dotyczących modernizacji floty i wyboru paliwa. W horyzoncie długoterminowym wodór i amoniak uzyskały najwyższe oceny jako paliwa przyszłości, zdolne do spełnienia najbardziej rygorystycznych norm środowiskowych, jednak ich wdrożenie zależy od dostępności infrastruktury oraz wsparcia politycznego i finansowego. LNG i metanol pozostają korzystnymi paliwami przejściowymi, zwłaszcza w żegludze regionalnej, ze względu na dostępność infrastruktury i relatywnie niższe koszty wdrożenia, choć w perspektywie 2050 mogą nie zapewniać wystarczającej zgodności z przepisami. Zastosowanie metamodelu integrującego aspekty techniczne, środowiskowe, ekonomiczne i regulacyjne umożliwia realistyczną symulację różnych scenariuszy decyzyjnych i powinno być stosowane w strategicznym planowaniu energetycznym flot. Rekomenduje się kontynuację badań nad technologiami wspierającymi dekarbonizację, w tym nad ogniwami paliwowymi, metodami magazynowania wodoru i oczyszczania emisji z paliw zawierających azot. Władze publiczne powinny natomiast intensyfikować wsparcie dla transformacji energetycznej żeglugi, poprzez inwestycje w infrastrukturę, instrumenty finansowe oraz harmonizację przepisów międzynarodowych i krajowych.

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STUDY ON THE IMPACT OF INTERNATIONAL EMISSION STANDARDS ON THE CHOICE OF ZERO-EMISSION FUELS IN SHIPPING

S u m m a r y

This paper analyses the influence of international and regional emission regulations, such as MARPOL Annex VI, the IMO GHG Strategy, FuelEU Maritime, and the EU ETS system, on the selection of alternative fuels in maritime shipping. The main objective of the study was to examine how legal standards affect shipowners' investment decisions regarding zero-emission propulsion technologies. An original decision-making metamodel was developed and applied, integrating technical, environmental, economic, and legal aspects. The model included operational parameters of ships, life cycle assessment (LCA) of fuels, compliance with key indicators (EEDI, EEXI, CII), and a Multi-Criteria Decision Analysis (MCDA) based on the Analytic Hierarchy Process (AHP). The results show that hydrogen and ammonia have the greatest potential to meet long-term regulatory requirements, provided that sufficient infrastructure and policy support are in place. LNG and methanol, on the other hand, remain economically viable transitional options, particularly in regional shipping contexts. The analysis confirms that fuel choice must be based not only on cost considerations but also on the ability to comply with increasingly stringent emission regulations. The developed model can support strategic investment planning in the maritime sector, facilitating the decarbonisation of fleets towards 2030–2050.

Keywords: MCDA, LCA, hydrogen, ammonia, LNG, methanol

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ASSESSMENT OF THE TECHNICAL CONDITION OF PIPELINE SYSTEMS FOR HYDROGEN MIXTURE TRANSPORTATION US-ING THE ENERGY APPROACH

A methodology has been developed for assessing the stress-strain state in tubular specimens under the influence of combined external loading and hydrogen-containing environments. The stress and strain distribution in the specimen was calculated using the finite element method A series of experimental studies was conducted on the tensile behavior of tubular cylindrical specimens, taking into account the effect of hydrogen. The material resistance under mechanical loading and hydrogen exposure was determined based on the energy approach using the digital image correlation (DIC) method of speckle patterns. Complete deformation diagrams were plotted for 17G1S steel, and the specific fracture energy was determined as an invariant characteristic of the material's resistance to deformation and fracture. It was established that the specific fracture energy in hydrogen for 17G1S steel is 7–8 times lower than that of the initial material. At the same time, it was shown that the concentration of hydrogen absorbed by the metal increases by 5–6 times.

Keywords: strength**,** the optical-digital correlation of speckle images (ODC-SI) method**,** hydrogen degradation, true deformation, true stress, fracture energy

1. Introduction

Hydrogen in contact with metal structures alters their strength and durability.

During the operation of pipeline systems under the influence of a hydrogen-containing environment and working pressure, defects form in the metal. Atomic hydrogen penetrates into the voids of these defects and molecularizes [1]

Molecularized hydrogen obstructs dislocation movement and generates additional stresses within the voids, affecting the material's resistance to deformation and fracture.

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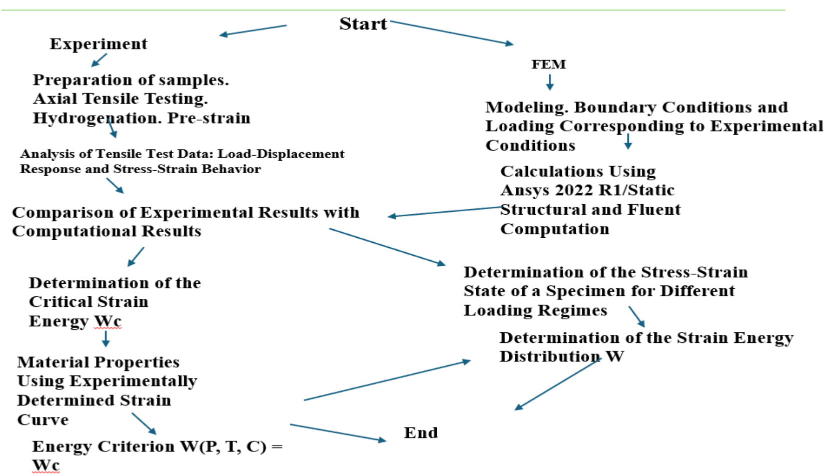
As a result, the material's strength and deformation characteristics are altered, leading to hydrogen-induced structural inhomogeneities in localized volumes of the material, ultimately reducing the load-bearing capacity of the elements.

Thus, addressing the changes in the load-bearing capacity of pipeline systems under operational conditions is critical. Since pipeline systems operate under mechanical loads and in a hydrogen-containing environment, it is essential to evaluate their operability based on the analysis of the stress-strain state in localized material volumes.

To address this, the study proposes assessing the reliable performance of gas transport pipeline systems using an energy-based criterion.

2. Application of an Energy Criterion to Assess the Load-Bearing Capacity of Pipeline Systems in Hydrogen-Containing Environments.

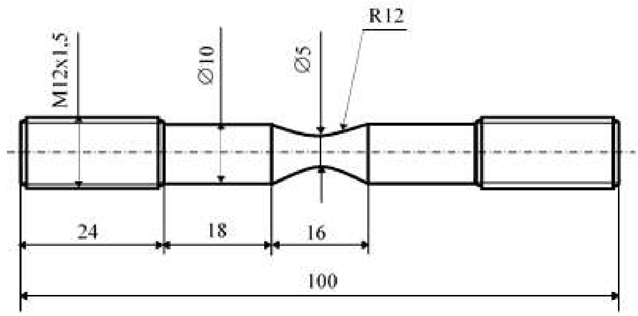
The proposed approach [2] comprehensively integrates experimental research with the results of mathematical modeling (Its algorithm is presented in Fig. 1). In the first stage, a series of experimental studies were conducted on the uniaxial tension of a modified Bridgman specimen (Fig.2). Deformation curves were constructed under the influence of loading and hydrogen in a localized volume using the optical-digital correlation of speckle images (ODC-SI) method. Numerical simulations were performed using ANSYS 2022R1, specifically the Static Structural solver on the Workbench 2022R1 platform. Considering the symmetry of the specimen, a three-dimensional model was developed (Fig.3). The finite element mesh in the specimen's neck region consisted of 132345 nodes and tetrahedral elements.



Rys.1. Algorytm procedury badawczej [2]

Fig.1. Research procedure algorithm [2]

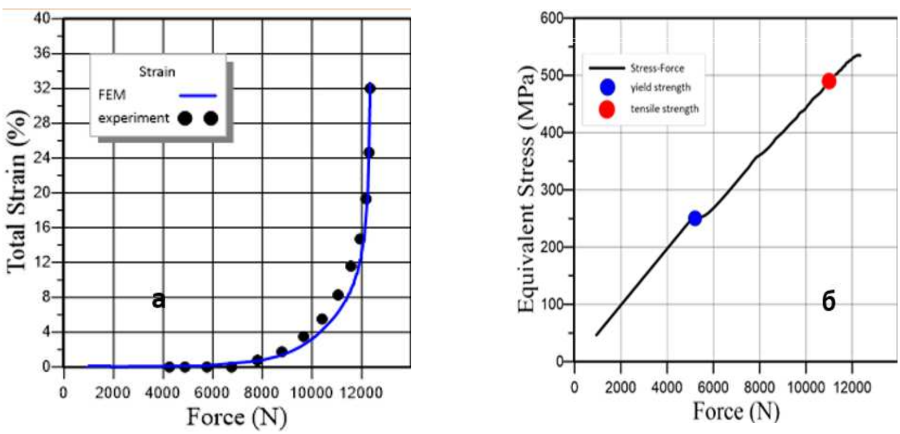
For each loading regime and hydrogen exposure condition, the fracture stress was determined. In the second stage, a 3D model of the Bridgman specimen was developed, and the energy of elastic-plastic deformation and damage evolution on the surface and within the volume of the specimen was calculated.



Rys.2. Rysunek zmodyfikowanej próbki Bridgmana [9]

Fig.2. Drawing of the modified Bridgman specimen [9]

To verify the proposed model, the authors [9] comparison was made between the experimentally determined deformation values e, obtained using the ODC-SI method, and the applied load (Fig.3 a). Additionally, a graph of the equivalent stress versus external load N under the tensile loading scheme of a cylindrical specimen was constructed (Fig. 3 b).



Rys.3. Wykres odkształcenia *e* w funkcji przyłożonego obciążenia: krzywa - dane uzyskane na podstawie modelu; punkty - wyniki uzyskane eksperymentalnie (a) [9] oraz Wykres zmian naprężenia zastępczego w funkcji obciążenia zewnętrznego N w schemacie obciążenia rozciągającego próbki cylindrycznej (b) [9]

Fig.3. Graph of the strain *e* versus applied load: curve – data obtained based on the model; points – results obtained experimentally (a) [9] and Graph of the variation of equivalent stress versus external load N under the tensile loading scheme of a cylindrical specimen (b) [9]

The research was conducted on samples made of 17G1S steel. Deformation was recorded in two directions:

$$e_x = \frac{du}{dx} + \frac{1}{2}\left[\left(\frac{du}{dx}\right)^2 + \left(\frac{dv}{dx}\right)^2\right]$$

$$e_y = \frac{du}{dy} + \frac{1}{2}\left[\left(\frac{du}{dy}\right)^2 + \left(\frac{dv}{dy}\right)^2\right], \quad (1)$$

where: e_x - the strain in the direction of the x-axis,

e_y - the strain in the direction of the y-axis.

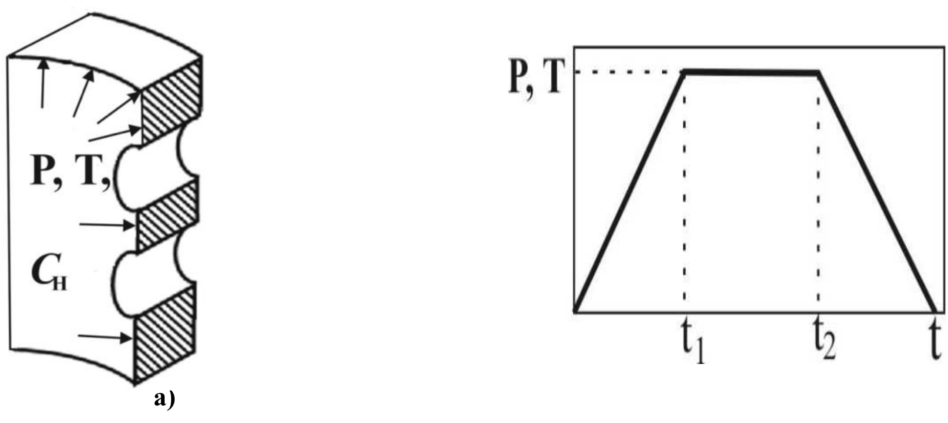
The true stresses were determined based on the following formula:

$$\sigma_e = \left\{\frac{1}{2}(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right\}^{\frac{1}{2}}, \quad (2)$$

where: σ_e- true stress,

$\sigma_1, \sigma_2, \sigma_3$ - principal stresses

The energy-based approach for assessing the technical condition of pipelines during hydrogen mixture transportation was proposed. The essence of this approach is as follows: let us consider a body with stress concentrators (Fig. 4a), subjected to mechanical loading while simultaneously exposed to a hydrogen environment and high temperature (Fig. 4b).



Rys. 4. Ciało z koncentratorami naprężeń poddane połączonemu działaniu obciążenia mechanicznego i wysokociśnieniowego, wysokotemperaturowego środowiska wodorowego (a) [10] oraz schemat wpływu wysokociśnieniowego i wysokotemperaturowego wodoru na ciało z koncentratorami naprężeń (b) [10].

Fig.4. A body with stress concentrators subjected to the combined action of mechanical loading and a high-pressure, high-temperature hydrogen environment (a) [10] and a diagram of the effect of high-pressure and high-temperature hydrogen on a body with stress concentrators (b) [10]

Under such conditions, the material deforms in a way that leads to the formation of regions near stress concentrators where deformation occurs at stress levels exceeding the yield strength, resulting in damage. This, in turn, affects the metal's resistance, which is associated with a change in fracture energy. Thus, if the specific energy of elastic-plastic deformation (of the local volume) W(P, T, C), under the influence of force P, temperature T, and absorbed hydrogen concentration C_H, reaches the critical value W_c^H, fracture will occur.

$$W(P,T,C_H) = W_c^H, \tag{3}$$

As a parameter of energy damage ω, the ratio of the elastic-plastic deformation energy of the local volume of the material, W, to its critical value, W_c, in a hydrogen environment is taken:

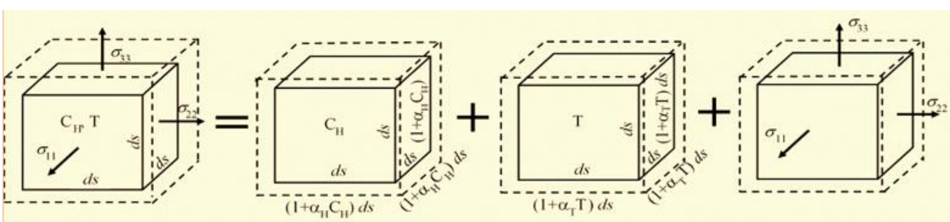
$$\omega = \frac{W(x,y,z,t)}{W_c}, \tag{4}$$

In the absence of damage in the material, before the application of loads, ω(t=0) = 0. The failure condition of the body corresponds to the case: ω (t = t∗) = 1 (where t∗ is the time that defines the durability of the body).

In our study, it is assumed that the influence of hydrogen concentration on the stress-strain state can be modeled based on the principle of superposition; that is, the increment of total strain during sample loading is given by over the time interval Δt is equal to the sum of the increments of strain due to hydrogen concentration C_H, the temperature component T, and the external load σ_{11} (Fig. 5)

$$\Delta\varepsilon ij = \Delta\varepsilon_{ij}^e + \Delta\varepsilon_{ij}^H + \Delta\varepsilon_{ij}^T, \tag{5}$$

where $\Delta\varepsilon_{ij}^e$ - the strain increment from loading,
$\Delta\varepsilon_{ij}^H$ - strain change as a function of hydrogen concentration,
$\Delta\varepsilon_{ij}^T$- strain change as a result of temperature influence

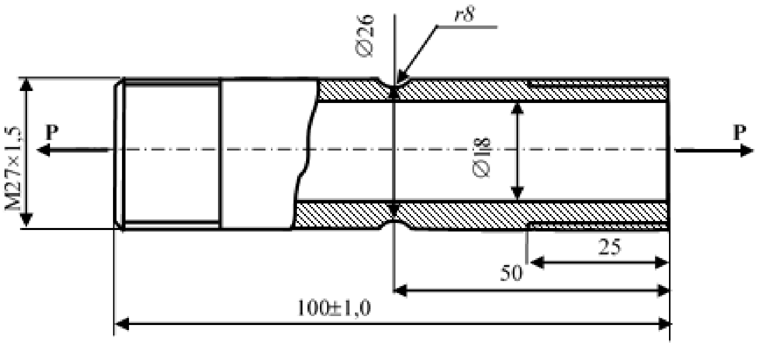


Rys. 5. Model wpływu stężenia wodoru na stan naprężenia i odkształcenia z wykorzystaniem zasady superpozycji.

Fig.5. A model of the influence of hydrogen concentration on the stress–strain state using the principle of superposition.

3. Methodology for Determining the Specific Fracture Energy of 17G1S Steel Considering the Influence of Gaseous Hydrogen

For the experimental studies, tubular specimens were fabricated from 17G1S steel (Fig. 6).



Rys. 6. Rysunek próbki rurowej [11]

Fig.6. Drawing of the tubular specimen [11]

The first batch of specimens was tested under uniaxial tension using the EUS-40 tensile testing machine. During the tests, the tensile force P was recorded using the machine's built-in dynamometer at a crosshead displacement rate of 2,0x10 mm/s.

Simultaneously, during the specimen's tensioning, displacement was recorded at the bottom of the concentrator and on the cylindrical surface using the optical-digital correlation of images (ODC-SI) method. The images obtained via ODC-SI were processed using an industrial Toupcan USMOS 1000 KPA camera with a Xenonlan lens. The camera was mounted on the testing machine platform and moved in unison with the movable grip.

Based on the research results, the true strain values were calculated using equations (6) and (7), as well as the elastic deformation energy (8), the specific elastic-plastic deformation energy (9), and the material's specific fracture energy $\overline{W}_c$ (10).

$$e_{xx} = \frac{\partial u}{\partial x} + \frac{1}{2}\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial x}\right)^2\right]$$

$$e_{yy} = \frac{\partial v}{\partial y} + \frac{1}{2}\left[\left(\frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2\right] \qquad (6)$$

where: e_{xx}, e_{yy} - values of true strain in the x and y directions.

$$e = \sqrt{e_{xx}^2 + e_{yy}^2}, \tag{7}$$

$$W_n = \frac{1}{2} S_n \cdot \varepsilon_n, \tag{8}$$

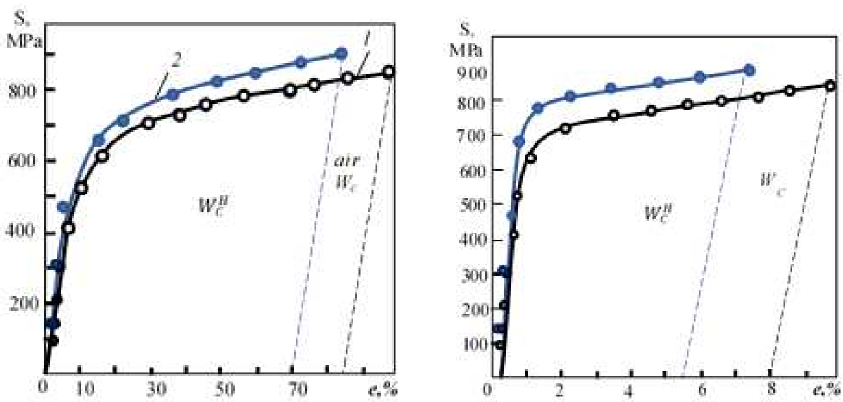
where: W_n - energy of elastic deformation
S_n - stress
ε_n - magnitude of engineering strain

$$W(x,y,z) = \int_0^e S(e)de, \tag{9}$$

where: $W(x,y,z)$ - energy of elastic-plastic deformation

$$W_c = \int_0^{e_c} S(e)de - \frac{1}{2} S_n \varepsilon_n, \tag{10}$$

The true stresses S_i were determined at each loading stage P_i accounting for changes in cross-sectional narrowing. Based on the test results, a true fracture diagram was constructed (Fig.7, Curve 1).



Rys. 7. Wykres rzeczywistego pękania próbek rurowych ze stali 17G1S (krzywa 1) i próbek wstępnie uwodornionych z fazy gazowej w temperaturze 400 °C (krzywa 2) (a) oraz wykres badań próbek utrzymywanych w wodorze w temperaturze 400 °C przez 24 godziny (b)

Fig.7. True fracture diagram of tubular specimens of 17G1S steel (curve 1) and specimens pre-hydrogenated from the gas phase at 400 °C (curve 2) (a) and diagram of tests on specimens held in hydrogen at 400 °C for 24 hours (b)

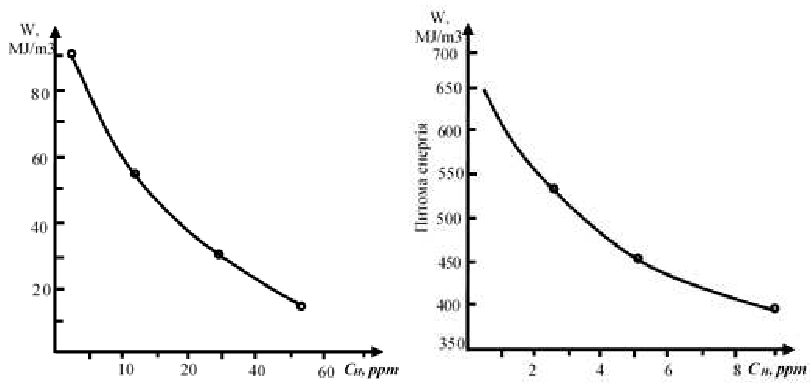
Figure 7a shows the true fracture diagram of tubular specimens made of 17G1S steel in air (curve 1). A similar study was conducted on a specimen of the same material that had been pre-hydrogenated from the gas phase at a temperature of 400°C. The test results for specimens exposed to hydrogen at 400°C for 24 hours are presented in Figure 7 (a) (curve 2). The fracture energy was calculated for both testing scenarios using equation (10), based on the complete fracture diagrams.

It was established that the specific fracture energy of pre-hydrogenated specimens decreases, while the true stress increases by 10% and the ultimate strain decreases by 15%.

Figure 7b shows the true stress–strain diagrams of tested specimens that were pre-deformed to 60% of the true fracture strain and subsequently exposed at 400°C in air (curve plotted using points (o)) and in gaseous hydrogen (curve plotted using points (•)).

It was demonstrated that the specific fracture energy of 17G1S steel in hydrogen without prior deformation is 20% lower than in air, while the critical strain is reduced by 35%. The true stress values in hydrogen are 5% higher than in air, indicating hydrogen-induced embrittlement of 17G1S steel. Pre-plastic deformation of the specimens to 60% of the true fracture strain reduces the specific fracture energy by a factor of 5. The ultimate strain after pre-deformation in a hydrogen environment decreases by a factor of 5.5 compared to air.

Based on the research results, dependencies were constructed showing the variation in the specific fracture energy of specimens depending on the concentration of absorbed hydrogen under different hydrogenation conditions and levels of prior true deformation (Figs.8 a, b).



a) b)

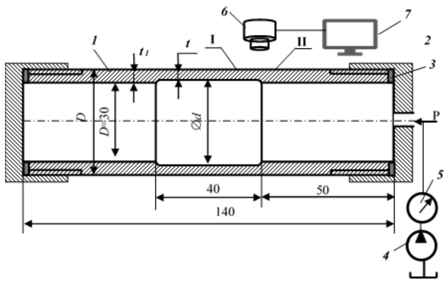
Rys.8. Zmiana energii właściwej pękania w zależności od stężenia wodoru w różnych warunkach uwodornienia i wcześniejszych rzeczywistych poziomach odkształcenia (a), (b)

Fig.8. Variation of specific fracture energy vs hydrogen concentration under different hydrogenation conditions and prior true strain levels (a), (b)

It was established that as the specific fracture energy of 17G1S steel specimens decreases, the hydrogen concentration in the fracture zone increases.

A method was developed to assess the degree of damage by comparing the specific deformation energy of a pipeline section in an undamaged state to that after prolonged operation.

For this purpose, tests were conducted using tubular specimens with grooves under internal hydrogen pressure, which simultaneously served as test chambers (Fig. 9).



Rys. 9 Komora próbki do prób rozciągania w warunkach wewnętrznego wodoru pod wysokim ciśnieniem

Fig.9. Specimen chamber for tensile testing under internal high-pressure hydrogen conditions

For this purpose, a study was conducted by testing tubular specimens with a groove (area I) under internal hydrogen pressure, which simultaneously served as the test chamber (Fig. 9). Under internal pressure from the hydraulic unit 4, deformation occurs in sections I and II of the sample's walls. At different levels of internal pressure from the unit, displacements on the outer surface of the sample were recorded using the optical coordinate measurement system (OCMS), and the magnitude of deformation in the two sections was calculated. Based on the deformation values and the true fracture diagram for 17G1S steel, the specific deformation energy was determined. During the loading of the sample with internal pressure, the local deformation over a base length of 0.5 mm was measured on sections I and II (with different wall thicknesses) using video camera 6 and recorded on computer 7. Based on the deformation values in two sections with wall thicknesses t_1 and t_2 the specific deformation energy is determined using the true fracture diagram of a tubular 17G1S steel specimen in air (Fig. 7a). A similar deformation measurement procedure is carried out after reducing the wall thickness by machining the inner surface. For different wall thickness ratios of the specimen at constant pressure, the specific deformation energy is determined.

The degree of energy-related damage is established by the ratio of the specific deformation energy to the specific fracture energy of 17G1S steel.

$$\omega = \frac{W_n}{W_c}, \tag{11}$$

Table 1 presents the results of experimental studies conducted on tubular specimens with different wall thicknesses. For each wall thickness ratio, 3 to 5 specimens were tested, with the measurement error not exceeding 5%.

Tabela 1 Zmiana energii odkształcenia w zależności od grubości ścianki

Table 1 Variation of deformation energy depending on the wall thickness

Pressure, MPa	D, mm	D_1, mm	d_2, mm	t, mm	W_e, %	W, MJ/m3
1	*2*	*3*	*4*	*5*	*6*	*7*
10,0	40	30	30	5	5	380
	40	30	32	4	4	450
	40	30	34	3	3	630

4 Summary

An energy-based approach has been developed to assess the technical condition of pipes and 17G1S steel during the transportation of hydrogen-containing mixtures:

1) It has been established that the specific fracture energy of 17G1S steel decreases by 70–90% under the influence of hydrogen.
2) The concentration of absorbed hydrogen in the metal depends on the degree of elastic-plastic deformation and increases 5–6 times compared to the initial state for 17G1S steel.
3) The specific fracture energy is found to depend on the degree of prior elastic-plastic deformation.
4) A theoretical-experimental approach has been proposed to evaluate the damage level of the pipe wall due to the combined effects of mechanical loading and a hydrogen-containing environment.
5) The developed methodology involves assessing the wear degree of the inner pipe wall based on the magnitude of local deformation, determined using an optical-digital correlator on the outer wall and the calculated elastic-plastic deformation energy.

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OCENA STANU TECHNICZNEGO SYSTEMÓW RUROCIĄGÓW DO TRANSPORTU MIESZANINY WODORU Z WYKORZYSTANIEM PODEJŚCIA ENERGETYCZNEGO

S t r e s z c z e n i e

Opracowano metodologię oceny stanu naprężenia i odkształcenia w próbkach rurowych pod wpływem połączonego obciążenia zewnętrznego i środowiska zawierającego wodór. Rozkład naprężeń i odkształceń w próbce został obliczony przy użyciu metody elementów skończonych. Przeprowadzono serię badań eksperymentalnych nad rozciąganiem cylindrycznych próbek rurowych, z uwzględnieniem wpływu wodoru. Odporność materiału pod obciążeniem mechanicznym i ekspozycją na wodór została określona w oparciu o podejście energetyczne przy użyciu metody cyfrowej korelacji obrazu (DIC) wzorców plamkowych. Wykreślono pełne wykresy odkształceń dla stali 17G1S i określono energię właściwą pękania jako niezmienną charakterystykę odporności materiału na odkształcenia i pękanie. Ustalono, że energia właściwa pękania w wodorze dla stali 17G1S jest 7-8 razy niższa niż dla materiału wyjściowego. Jednocześnie wykazano, że stężenie wodoru absorbowanego przez metal wzrasta 5-6-krotnie.

Słowa kluczowe: wytrzymałość**,** metoda optyczno-cyfrowej korelacji obrazów plamkowych (ODC-SI)**,** degradacja wodoru, odkształcenie rzeczywiste, naprężenie rzeczywiste, energia pękania

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CARBON DIOXIDE METHANATION IN PtG TECHNOLOGY

Carbon dioxide methanation as part of Power-to-Gas (PtG) technology is one of the most promising processes today, as it simultaneously solves two important environmental problems: it reduces carbon dioxide emissions by using it in the hydrogenation process to methane and helps balance the fluctuations of electricity from renewable sources (RES), which in turn is important for the stability of the electricity grid. An obstacle to the widespread use of this technology is its low microeconomic efficiency. This paper proposes a new method of conducting carbon dioxide methanation in a tube reactor, consisting of cyclically carrying out this process from the standby to the operating state and vice versa. This eliminates energy losses associated with the turning off and restarting of the equipment and improves the energy process. This way of conducting the process allows to reduce the consumption of energy needed to heat the gas stream and the apparatus by up to 70%, in relation to the consumption of this energy in the process in which the apparatus is periodically switched on and off.

Keywords: hydrogen, hydrogenation, methane, Sabatier reaction

1. Intoduction

1.1. Sabatier reaction

The catalytic hydrogenation reaction of carbon dioxide was based on research conducted by two scientists, Paul Sabatier (Nobel Prize winner in chemistry) and Jean-Baptiste Sendersen. The aim of this study was to determine the effect of reduced metals on the hydrogenation of unsaturated compounds, such as acetylene or ethylene [4]. This method was soon used to hydrogenate many other classes of compounds containing unsaturated bonds, aldehydes, ketones, nitriles, and these reactions were carried out in the presence of reduced nickel. Paul Sabatier investigated and described, among others, methods of catalytic cracking of hydrocarbons, synthesis of methanol and methane in the presence of nickel. Currently, it is accepted that the Sabatier reaction is defined as the catalytic hydrogenation of carbon dioxide to methane and water (reaction 1).

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$$CO_2 + 4H_2 \leftrightarrows CH_4 + 2H_2O \quad (1)$$

$\Delta H_{298K} = -165$ kJ/mol

Sabatier's reaction in Power to Gas technology

Carbon dioxide methanation as part of Power-to-Gas (PtG) technology is one of the most promising processes today. It solves two important environmental problems: it reduces carbon dioxide emissions by using it in the hydrogenation process to methane and it helps to balance the fluctuations of electricity from renewable sources (RES). Its product is methane, a gas with versatile applications.

Despite the passage of time, the detailed mechanism of the Sabatier reaction on a nickel catalyst has not been precisely determined. The presented carbon dioxide reduction reaction (reaction 1) can proceed according to different mechanisms, depending on the nickel catalyst used, with two being the most popular in the literature [9]. The first assumes that carbon dioxide is converted into an intermediate product, carbon monoxide, which is then hydrogenated to methane. The second assumes direct hydrogenation of carbon dioxide to methane.

More popular among researchers is the mechanism, which is the methanation of carbon dioxide by an intermediate product, which is carbon monoxide. It is typically described by simple overall reactions 2 and 3.

$$CO_2 + H_2 \leftrightarrows CO + H_2O \quad (2)$$

$\Delta H_{298K} = +41$ kJ/mol

$$CO + 3H_2 \leftrightarrows CH_4 + H_2O \quad (3)$$

$\Delta H_{298K} = -206$ kJ/mol

In accordance with contemporary knowledge, the detailed mechanism of these reactions consists of many steps. Knowledge of the real mechanism is not necessary to conduct the process, but it makes it easier to refine the conditions of its conduct so as to obtain the desired results, e.g. maximum process speed (reduction of the size of the equipment), high selectivity (no by-products), and improvement of economic effects (maximization of profit or reduction of costs).

The advantages of using the Sabatier reaction in PtG technology are as follows:

1) Reduction of carbon dioxide emissions (reaction 1)
2) Conversion of excess electricity into chemical energy, this is one of the possible answers to the question: "How to store energy that windmills or photovoltaics produce for several hours a day in too large quantities?" This problem is a key barrier to the development of renewable energy. Every year since 2023, Poland had to partially disconnect RES sources from the power grid to maintain its stability. The constantly growing number of RES sources will increasingly threaten the grid overload and the so-called blackout.

Electricity can be used to produce green hydrogen through water electrolysis. To obtain one kilogram of hydrogen, you need to use about 50-60 kWh of electricity and 8-10 liters of water (reaction 4).

$$2H_2O \rightarrow 2H_2 + O_2 \quad (4)$$

A reduction reaction (reaction 5) then takes place in the cathode, in which gaseous hydrogen and OH^- ions are formed.

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^- \quad (5)$$

Oxidation (reaction 6) takes place at the anode, which produces molecular oxygen, protons (hydrogen cations), and electrons.

$$2H_2O \rightarrow O_2 + 2H^+ \quad (6)$$

3) Obtaining methane – a valuable chemical or energy raw material (SNG, reaction 1).

It is worth noting that all the advantages given profits are carried out simultaneously.

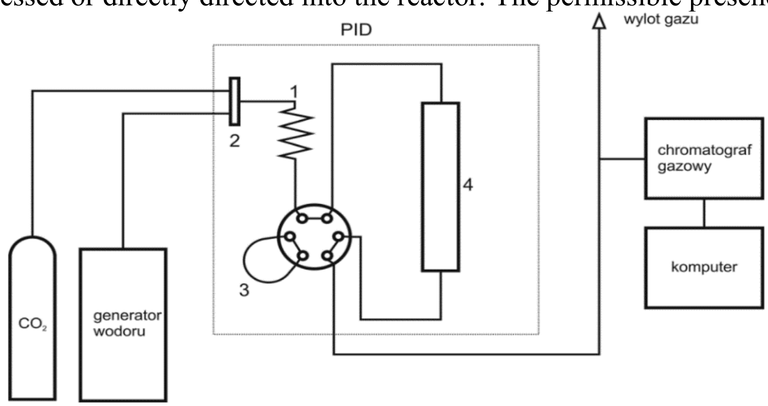
The conditions recommended in the literature for the carbon dioxide methanation are a temperature of 200 – 500°C and the pressure of 1 to 30 bar [6, 9, 10]. Increasing the temperature accelerates the course of the reaction, but at the same time promotes the opposite reaction, i.e. the breakdown of methane. Increasing the pressure promotes the formation of the product; Near-atmospheric pressure favors the opposite reaction, but this is only relevant at higher temperatures. For this reason, the pressure range is commonly used in carbon dioxide methanation reactions. The nickel content in the catalyst used should be up to 25%. The amount of methane in the postreaction mixture depends on the ratio of the reactants, i.e. hydrogen to carbon dioxide. Increasing the number of moles of hydrogen causes an increase in the amount of methane in the post-reaction mixture. The reaction is usually carried out with a ratio of substrates in the gas inlet stream close to stoichiometric (i.e. $H_2:CO_2 = 4:1$), but it should be remembered that due to possible diffusion limitation, this ratio may vary at the catalyst. The addition of water vapor in the inlet mixture of substrates leads to a slight decrease in the degree of carbon dioxide reaction, with no noticeable difference in selectivity and efficiency for methane. The methane content in the inlet mixture does not significantly affect the degree of carbon dioxide reaction [7].

The low microeconomic efficiency is an obstacle to the widespread use of the carbon dioxide methanation process. From Martin Lambert's publication "Power-to-Gas: Linking Electricity and Gas in a Decarbonising World?" [5], it is known that in Germany, in Werlte, there is a pilot plant consisting of three alkaline electrolytic cells with a capacity of 2 MW, which, using surplus renewable energy, produce up to 1300 Nm^3 hydrogen per hour. The adjacent biogas plant produces biomethane and carbon dioxide. Separated carbon dioxide reacts with hydrogen produced in electrolytic cells, allowing up to 325 Nm^3 methane per hour to be obtained per hour. The installation is switched on and off on average 33 times a month, which is not the optimal way to conduct the process in a tube reactor. According to the principles of reactor engineering, this type of reactor achieves the highest productivity under stationary operating conditions. Otherwise, reactor productivity drops and additionally energy losses are observed, among others, due to the need to warm and cool the apparatus (the typical operating temperature of the catalytic system is 300 – 400°C). For these reasons, efforts should be made to shorten the operating time of the reactor in nonstationary conditions. Therefore, a new method of conducting carbon dioxide in a tube reactor has been developed, consisting of cyclically carrying out this process from the standby regime of the operating regime and vice versa, which will allow the energy improvement of the process [8]. It can be the basis for creating new methanation installations or improving existing ones.

2. Experimental part

Carbon dioxide methanation process

A tubular reactor made of quartz glass or stainless steel, with a nickel catalyst with an active substance (nickel) content in the range of 16 – 54 wt%, is supplied with gaseous phase reactants: carbon dioxide, hydrogen or inert gas. Carbon dioxide, depending on the source of origin and possible contaminants, can be preprocessed or directly directed into the reactor. The permissible presence of



Rys. 1. Schemat aparatury; 1 - wstępny podgrzewacz gazu, 2 - zespół masowych kontrolerów przepływu, 3 - zawór sześciodrożny z bocznikiem, 4 - reaktor rurowy z płaszczem grzewczym

Fig. 1. Scheme of the measurement system; 1 - gas preheater, 2 - mass flow controllers unit, 3 - six-way valve with bypass, 4 - tubular reactor with heating

inert substances in the inlet stream is 0 – 30% vol. Conditions for conducting the carbon dioxide methanation process depending on the mode of conduct of the process (readiness or operation): carbon dioxide in a mixture with hydrogen 1 – 18% vol., flow velocity calculated on an empty reactor at STP 0.0106 – 0.0212 m/s, pressure 0.15 – 0.25 MPa, temperature 200 – 310°C. The water released during the reaction, after liquefaction, is removed from the system, and the post-reaction gas mixture is subjected to chromatographic analysis to determine the degree of carbon dioxide reaction [8]. The diagram of the equipment used is shown in Figure 1. The electricity consumption during the methanation process is monitored by a measure at one-minute intervals.

Operating Regime Parameters

Operating regime parameters are as follows:

1) carbon dioxide concentration – from 14% to 18% vol.,
2) temperature – from 255°C to 310°C,
3) the flow rate of the reactant mixture calculated on an empty reactor at STP – from 0.016 m/s to 0.022 m/s,
4) higher pressure, if necessary.

Standby Parameters

Standby regime parameters are as follows:

1. carbon dioxide concentration – from 0% to 14% vol.,
2. temperature – from 200°C to 255°C,
3. the flow rate of the reactant mixture calculated on an empty reactor at STP – from 0.01 m/s to 0.016 m/s,
4. possibly lower pressure 0.15 MPa to 0.25 MPa.

2.2. Overview of the process of carbon dioxide methanation

The duration of the reactor's stay in operating or standby regime depends on the availability and price of electricity. In the event of low energy availability or high energy prices, the process is carried out in standby mode, which is characterized by operating parameters from the lower part of the process window (low carbon dioxide concentration, low temperature, or low pressure). With high energy availability (e.g. from RES), the process is carried out in the operating mode, which corresponds to higher values of parameters from the process window. Single-tube reactors can be combined into batteries to increase process productivity. The transition from standby to operation mode is initiated by a step increase in the concentration of carbon dioxide at the inlet to the reactor, an increase in the flow rate, and, if necessary, the supply of additional thermal energy to the system. Due to the low inertia, it is recommended to use electric heaters. On the other hand, the transition from the operating mode to the standby mode is initiated by a step reduction in the concentration of carbon dioxide at the inlet to the reactor, a decrease in the flow velocity, which results in a rapid reduction in the amount of heat generated, and a decrease in the temperature of the system. To improve the stability of the system and reduce the standby time, it is envisaged that the carbon dioxide concentration can be temporarily reduced to zero. The system pressure can remain the same during the mode change, or it can vary according to the scheme: standby mode, low operating pressure in the system, operating mode – high operating pressure.

3. Summary

This method of conducting the methanation process allows one to reduce the consumption of energy needed to heat the gas stream and the apparatus by up to 70%, in relation to the consumption of this energy in the process in which the apparatus is periodically switched on and off. It should be noted that under favorable conditions of energy availability, the reactor (or battery) can operate continuously in operation. Due to the lack of experience of the team members in this area, no simulation of the actual economic effects of the application of the invention was performed. Profits are estimated only on direct measurements of the amount of electricity consumed.

The work on improving the operation of the process is still ongoing. A research reactor with a diameter of 25 mm was made (which corresponds to approximately six times the volumetric rate of the one reactor compared to the previously used). Preliminary studies are being carried out to improve the economic efficiency of the process by extending the range of hydrogen quantities used. Catalysts with a different nickel content are being tested. A method to increase the reactivity of carbon dioxide using electromagnetic waves is being prepared for experimental tests.

It should be noted that interest in the practical application of the Sabatier reaction is constantly growing, as evidenced by the increasing number of patents granted in recent years [1–3, 11, 12].

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METANIZACJA DWUTLENKU WĘGLA W TECHNOLOGII PTG

Streszczenie

Metanizacja dwutlenku węgla, w ramach technologii Power-to-Gas (PtG) jest jednym z najbardziej obiecujących obecnie procesów, rozwiązuje bowiem jednocześnie dwa ważne problemy środowiskowe – ogranicza emisję dwutlenku węgla, poprzez jego wykorzystanie w procesie uwodornienia do metanu i pomaga zrównoważyć fluktuacje energii elektrycznej pochodzącej z odnawialnych źródeł (OZE), co z kolei ma znaczenie dla stabilności sieci elektrycznej. Przeszkodą w powszechnym zastosowaniu tej technologii jest jej mała efektywność mikroekonomiczna. W pracy zaproponowano nowy sposób prowadzenia metanizacji dwutlenku węgla w reaktorze rurowym, polegający na cyklicznym przeprowadzaniu tego procesu go ze stanu gotowości do stanu pracy i odwrotnie. Powoduje to wyeliminowanie strat energii związanych z wyłączaniem i ponownym uruchamianiem instalacji oraz usprawnienia energetyczne proces. Taki sposób prowadzenia procesu pozwala na redukcję zużycia energii potrzebnej do ogrzania strumienia gazu i urządzeń nawet do 70%, w stosunku do zużycia tej energii w procesie, w którym instalacja jest okresowo włączana i wyłączana.

Słowa kluczowe: wodór, uwodornienie, metan, reakcja Sabatiera

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THE USE OF GREEN BONDS IN FINANCING HYDROGEN PROJECTS IN THE EUROPEAN UNION

The chapter examines the use of green bonds as a financial instrument to support hydrogen projects within the European Union's pursuit of climate neutrality by 2050. Green hydrogen, produced using renewable energy, plays a vital role in decarbonizing sectors that are difficult to electrify, such as heavy industry and transport. However, building a hydrogen economy requires significant investment, beyond the capabilities of public funding alone. Green bonds, whose proceeds must be allocated exclusively to environmentally beneficial purposes, offer a mechanism to attract private capital. The EU and its Member States such as Germany, France, the Netherlands, and Poland are actively developing this market. Examples like Gasunie and Air Liquide demonstrate growing investor interest in hydrogen-related projects. A SWOT analysis included in the chapter outlines key strengths (e.g., long-term financing, enhanced sustainability image), weaknesses (e.g., issuance costs, project uncertainty), opportunities (e.g., high investment demand, strong regulatory support), and threats (e.g., market volatility, political risk). The conclusion emphasizes that green bonds can become a cornerstone of hydrogen financing in the EU. While not a standalone solution, they complement grants, loans, and equity, and their importance is expected to grow as the hydrogen sector matures and sustainable finance markets expand.

Keywords: hydrogen, sustainable finance, low-carbon economy, energy transition, climate policy

1. Introduction

The European Union aims to achieve climate neutrality by 2050, which requires massive investment in energy transition and technological innovation. It is estimated that achieving the 2030 climate targets alone necessitates investments of around EUR 180 billion per year. Hydrogen, particularly so-called "green hydrogen" produced using renewable energy, is regarded as a key element of this transition, capable of helping decarbonize sectors that are hard to electrify, such as heavy industry, chemicals and transport. However, the large-scale development of a hydrogen economy requires significant financing, exceeding traditional public funding sources.

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is estimated that achieving the 2030 climate targets alone necessitates investments of around EUR 180 billion per year. Hydrogen, particularly so-called "green hydrogen" produced using renewable energy, is regarded as a key element of this transition, capable of helping decarbonize sectors that are hard to electrify, such as heavy industry, chemicals and transport. However, the large-scale development of a hydrogen economy requires significant financing, exceeding traditional public funding sources. Green bonds are an innovative financial instrument that can play a major role in mobilizing private capital for environmental projects, including hydrogen undertakings. The first green bond issuance in the world took place in Europe, the European Investment Bank issued a pioneering climate bond in 2007, inaugurating the practice of monitoring and reporting on the use of proceeds for green projects. Since then, the green bond market has experienced dynamic growth. In Europe, the value of green bond issuances has been rising continuously since 2014, and the total volume of European green bond issuances between 2014 and 2020 reached approximately about EUR 380 billion. Furthermore, Poland was the first country to issue sovereign green bonds. The debut issuance worth EUR 750 million took place in 2016, underscoring Europe's leading role in the development of this market.

In the context of growing financing needs for the hydrogen economy, green bonds appear to be a promising source of capital. They allow private investors to co-finance green projects, while simultaneously providing issuers with funds for hydrogen investments under favorable financial conditions. This paper discusses the use of green bonds in financing hydrogen projects in the European Union. It presents the definition of green bonds and the mechanisms of their operation, the significance and scale of financing hydrogen projects in the EU via this instrument, examples of specific green bond issuances dedicated to hydrogen projects in selected countries, the impact of EU climate regulations on financing hydrogen projects, a SWOT analysis of financing hydrogen projects by means of green bonds and conclusions on the prospects for the development of this financial instrument in the hydrogen sector.

2. Definition of green bonds and mechanisms of operation

Green bonds are debt instruments intended to finance projects that deliver environmental benefits. In other words, their distinguishing feature is the purpose of the issuance. Proceeds from such a bond must be used exclusively to finance, in whole or in part, environmentally friendly initiatives. According to the definition proposed by the Climate Bonds Initiative, a green bond is one whose proceeds are allocated to projects, which are good for environment.

From a financial-structure perspective, green bonds do not differ from traditional bonds, the issuer undertakes to redeem the bonds after a specified period and to pay interest, while the investor bears the issuer's credit risk, as with any standard bond. However, the mechanism of green bonds lies in the issuer's commitment to implement clearly defined environmental objectives. Hence, the key distinguishing feature is transparency regarding the use of the raised funds. Issuing green bonds typically requires preparing a so-called green bond framework, wherein the issuer specifies the categories of projects eligible for financing from the bond proceeds as well as the procedures for managing and reporting on the disbursement of those funds. The ICMA Green Bond Principles (GBP) serve as a market standard. Non-binding guidelines stating that a green bond should meet four fundamental criteria; use of proceeds exclusively for green projects, a transparent process for evaluating and selecting projects, separate management of proceeds (e.g., via a designated account or register), and reporting on the allocation and impact of the projects. In practice, issuers often seek external verification or a second-party opinion to confirm that their issuance framework meets the GBP and that the financed projects satisfy adopted environmental criteria, this helps prevent the appearance of environmental benefits that do not actually exist.

Oversight of the use of funds from green bonds is a crucial element of their operational mechanism. For instance, Gasunie (the Dutch gas network operator) emphasizes that the proceeds from its green bonds are recorded in a special register and can only be spent on predefined "green" objectives. Likewise, the city of Łódź in Poland, which issued green municipal bonds, had to ensure that the PLN 50 million raised would be used solely for two specific environmental projects (the modernization of water and sewage management and the development of low-emission public transport). These procedures provide investors with transparency and certainty that their capital is genuinely allocated to green investments, while also enforcing discipline on the issuer in achieving the environmental objectives of the issuance. Legally speaking, green bonds are standard debt securities, but their essence lies in the voluntary assumption by the issuer of additional obligations regarding the way the capital is used, along with acceptance of greater transparency and oversight of their environmental objectives.

3. The significance and scale of financing hydrogen prjocets in the EU through green bonds

Hydrogen has become one of the priorities of the EU's energy and climate strategy. The EU Hydrogen Strategy of 2020 and the REPowerEU plan of 2022 have set ambitious goals by 2030, the Union plans to achieve an annual production capacity of 10 million tons of renewable hydrogen and to import an additional 10 million tons. Fulfilling these objectives will require the installation of dozens of gigawatts in new electrolysis capacity as well as creating hydrogen transportation and storage infrastructure throughout Europe, entailing investments on the order of hundreds of billions of euros. According to estimates cited by Hydrogen Europe, globally the development of a clean hydrogen economy could require between USD 1.2 and 2.6 trillion in investment by 2050. Naturally, only a portion of this will apply to Europe but it is already evident that public funds alone will not suffice. Engaging private capital on an unprecedented scale is therefore essential and green bonds serve as a bridge between public objectives and the financial markets.

At the moment, financing hydrogen projects via green bonds is only beginning to gather momentum, yet it is growing in importance. In the early phase of the green bond market's development, projects related to energy, building energy efficiency and green transport predominated. Hydrogen projects constituted only a marginal share of the portfolio, mainly because of their early stage of technological maturity and lack of commercial scale. However, now that hydrogen investments in the EU are accelerating, the first large green-bond issues dedicated to hydrogen projects are emerging and the sector is seen as the next area of growth in green finance. According to Hydrogen Europe, of all the planned clean-hydrogen projects in the EU, only about 4% have so far reached the stage of a final investment decision, meaning that the overwhelming majority of investments are still seeking financing. This creates a substantial financing gap, which green bonds can partly fill by directing a flow of private capital to hydrogen projects.The scale of hydrogen financing via green bonds in the EU is currently counted in the low billions of euros but is on an upward trend. Both government issuances, in which part of the raised funds is allocated to hydrogen and specialized corporate bonds for hydrogen projects are beginning to appear. For example, under the NextGenerationEU recovery program, the European Commission plans to issue up to EUR 250 billion in green bonds to fund the environmental components of Member States' recovery plans. Many national recovery plans include hydrogen investments as a major item, implying that EU green-bond proceeds will indirectly flow to hydrogen projects. At the national level, countries such as Germany, France and the Netherlands include hydrogen spending in their green budget frameworks. In Germany, the sovereign green bonds fund, among other things, hydrogen technology research and international hydrogen market collaboration. In the Netherlands the green bond allocation report indicates that some of the proceeds went directly toward constructing the national hydrogen grid and supporting electrolyzer projects.

The importance of green-bond hydrogen financing is best demonstrated by the growing involvement of the private sector. Large European energy and industrial conglomerates are announcing plans for substantial green-bond issuances to fund their energy-transition projects, including hydrogen initiatives. For example, the German energy company RWE declares an intention to issue EUR 3–3.5 billion annually in green bonds on international markets by 2030, in order to fund its portfolio of renewables and hydrogen investments. This underscores the role this instrument is starting to play in the financing strategies of corporations involved in clean hydrogen. In conclusion, although green-bond financing of hydrogen projects in the EU is only now evolving, it already constitutes a significant channel for capital mobilization. In the coming years, its scale is likely to expand substantially as hydrogen projects mature and the green finance market continues to develop.

4. Examples of green bond issuances for gydrogen projects in the EU

To better illustrate the practical use of green bonds in financing hydrogen infrastructure, it is worth analyzing several specific examples of bond issuances from recent years in various EU countries.

A pioneering instance is the earlier mentioned Gasunie. The state-owned gas network operator in the Netherlands, which is responsible for building the national hydrogen transmission grid. In November 2023, Gasunie issued its first green bond worth EUR 300 million, with a maturity of 9.5 years, to fund energy-transition projects, chiefly the construction of the national hydrogen transmission system. This bond, carrying a coupon of 3.875%, met with enormous investor interest, demand exceeded supply by more than five times. The funds raised were allocated to the initial phases of constructing the hydrogen transmission network. Gasunie also declared that by the end of the decade it plans to invest over EUR 5.5 billion in new infrastructure for renewable gases with a significant portion expected to be financed through regular green-bond issuances. Notably, Gasunie's financing framework is closely aligned with European standards. The company created a Green Financing Framework, which received a positive review from an independent firm and was deemed consistent both with the ICMA Green Bond Principles and with the requirements of the European Union. This means that projects such as the Dutch hydrogen transmission network fulfill criteria, enhancing the credibility of these bonds in the eyes of investors.

The Dutch government also uses proceeds from sovereign green bond issuances to fund hydrogen projects. According to the 2023 report on green bond allocation, among the expenditures financed is the development of the national hydrogen infrastructure. The Netherlands aspires to become the first country in Europe to construct a complete hydrogen infrastructure by 2030 hoping to solidify its position as a crucial hub for renewable hydrogen trade. Including these expenditures in the portfolio financed by sovereign green bonds lowers the cost of financing for the state and signals to investors that the country is strategically developing low-carbon projects.

In France, an example of green-bond use in hydrogen can be found among private industrial conglomerates. French company Air Liquide issued a green bond worth EUR 500 million under its EMTN program. The purpose of the issuance is to finance flagship energy-transition initiatives, particularly in low-carbon hydrogen and "clean" industrial gases. The company highlighted that the bond proceeds would be devoted to developing installations for producing renewable hydrogen, carbon capture and utilization technologies and other activities reducing its carbon footprint. This is another consecutive green bond issued by Air Liquide and each garnered strong investor interest, reflecting market confidence in the company's sustainable development strategy. Air Liquide's issuance underscores that the industrial sector also employs green bonds to fund the transition of its processes. Meanwhile, since 2017 the French state has issued sovereign green bonds to finance various green budgetary expenditures and in recent years a portion of these funds has been directed at hydrogen innovations.

In Germany, the federal government has been issuing sovereign green bonds since 2020, which also finance hydrogen-related projects. According to the German Green Bond Framework, proceeds from green sovereign issues are allocated to five areas: transport, international cooperation, research and innovation, energy and industry, and agriculture and the environment. Under the category energy and industry, projects supporting the international development of the green hydrogen market and the use of hydrogen in industry are eligible for funding. For example, from the 2022 budget, around EUR 45.4 million was allocated to international hydrogen collaboration and close to EUR 200 million was allocated to hydrogen technology research and development. Moreover, German states and development banks are also involved in financing hydrogen projects. For instance, energy giant RWE is developing hydrogen projects with a combination of governmental grants and potential future green-bond issuances. RWE's announced series of global green-bond issuances is partly intended to fund hydrogen projects that the company is implementing across various European countries.

These examples reflect diversity in issuers and structures - from government bonds to state-owned companies, to private corporations. All share the goal of raising capital for hydrogen-related investments while ensuring a "green" label for investors. A common feature is compliance with the EU's sustainable finance guidelines.

5. The impact of EU climate policies and regulations on financing hydrogen projects

Over the past few years, the European Union has introduced various policies and regulations aimed at directing financial flows toward climate-focused projects. Two key regulatory instruments in this context are the EU Taxonomy and the European Green Bond Standard. These regulations significantly affect hydrogen-project financing, shaping which projects qualify as "green" and boosting the credibility of green bonds as a funding mechanism for such initiatives.

The EU Taxonomy is a system for classifying sustainable economic activities. It defines criteria that must be met for investments to be considered supportive of environmental goals. Concerning hydrogen, the Taxonomy sets specific requirements for producing low-emission hydrogen. According to the relevant technical screening criteria, hydrogen production can only be deemed sustainable if it is characterized by low greenhouse gas emissions. For hydrogen, the established benchmark is 3.0 kg CO_2 per 1 kg H_2. By comparison, so-called grey hydrogen from methane reforming without carbon capture emits about 10 kg CO_2/kg H_2. Thus, the Taxonomy effectively demands the use of zero-emission energy sources or carbon capture to qualify. Thanks to the EU Taxonomy, investors gain clarity about which hydrogen projects are genuinely "green." For an issuer of green bonds, this means that if they wish to attract abroad investor base and meet EU standards, their hydrogen projects financed through bonds must satisfy those requirements. Consequently, the EU Taxonomy serves as a reference framework for structuring green-bond programs, who aim to ensure the compliance of their funded projects.

The second regulatory component is the forthcoming European Green Bond Standard (EuGBS), an EU regulation establishing a voluntary standard for bonds labeled as "European green bonds." Under this regulation, any issuer wishing to use the label "European Green Bond" must fulfill stringent requirements. Among them ensuring that essentially 100% of proceeds are allocated to activities compliant with the EU Taxonomy. In addition, detailed disclosures and reporting are required, along with verification by an accredited external reviewer. Although the standard is voluntary, it is expected to become the gold standard in the market, representing best practices. Its significance for financing hydrogen projects is twofold. First, it enforces high quality in financed projects, excluding environmentally questionable investments from being marketed under green bonds and reducing the risk of greenwashing. Second, it enhances investor confidence and interest in this segment. Particularly for hydrogen projects, which often require a longer investment horizon and involve some technological risks, access to a wide pool of investors seeking stable, long-term commitments is vital. The European Green Bond Standard may facilitate issuances with longer maturities that match the return period of hydrogen investments, as it gives investors greater assurance regarding the genuine "green" credentials of these securities.

6. Methodology

The SWOT analysis is among the most frequently employed methods in strategic management, marketing and economic sciences. Its original form was described in the 1960s. The aim of a SWOT analysis is to capture comprehensively the internal factors (strengths and weaknesses) and external factors (opportunities and threats) that influence the situation of a given entity, this may be an organization, a sector, an investment project, or any other area in need of a multifaceted assessment.Its principal advantage lies in its simplicity, which in no way diminishes its effectiveness. The essence of the analysis is to identify and categorize all the major issues into four areas. A key step is compiling a list of factors in the aforementioned categories and then evaluating them in terms of their impact on the analysis objective. In the next stage, one often creates a SWOT matrix that juxtaposes individual elements to identify possible interactions, for example, how existing strengths can help exploit opportunities more fully or how weaknesses might amplify threats. The final outcome is a perspective that facilitates strategic decisions and recommendations, such as methods of leveraging advantages, mitigating risks, or countering vulnerabilities.

Although SWOT is a fairly universal method, it has been criticized for allowing oversimplification. Critics note that misapplication or the failure to incorporate empirical data can lead to overly general conclusions. Nevertheless, especially in economics and public management, its popularity stems from the need for a quick, comprehensive tool to evaluate. It is also helpful for new investment areas, where many unknowns exist, an example being the potential of financing innovative projects via green bonds.

7. SWOT analysis of financing hydrogen projects via green bonds

Strengths

1) Green bonds enable large-scale fundraising from private investors, supplementing public funds and corporate equity. For capital-intensive hydrogen projects, this is essential. Thanks to such additional sources, projects can be implemented faster and on a larger scale than if they relied solely on grants or bank loans.
2) Green-bond issuances often encounter high investor demand, which can lead to favorable pricing. The strong appetite is partly driven by the growing number of investment funds and financial institutions seeking assets that fulfill sustainability criteria.
3) Financing hydrogen projects through green bonds bolsters the issuer’s image as a sustainability leader. Issuers can demonstrate concrete climate-related initiatives to stakeholders, building reputation. The example of Łódź illustrates that the municipal green bond issuance strengthened the perception of the city as eco-responsible.
4) Issuing green bonds facilitates integrating hydrogen projects into the broader EU climate policy context. Projects meeting Taxonomy criteria may qualify for additional support or synergies. Moreover, green bonds reduce regulatory risk, if a project is financed as “green,” it has greater certainty regarding regulatory stability. Investors also see such projects as safer long-term bets, given policy backing for decarbonization.
5) Hydrogen infrastructure projects have lengthy timelines for both construction and operation. Green bonds, often issued with longer maturities, provide long-term financing aligned with the asset’s lifecycle, an advantage over, for

instance, short- or medium-term bank loans. Institutional investors with long-term horizons are keen on such issuances, ensuring stable financing over many years.

Weaknesses

1) Many planned hydrogen projects in the EU remain in a conceptual or pilot phase. Such projects entail a higher degree of technological and market uncertainty. Bond investors prioritize security and predictable cash flows, yet commercial business models for hydrogen are still evolving.
2) Preparing a green bond can be more time-consuming and expensive than a conventional bond. It requires drafting a green financing framework, engaging advisors for verification and providing ongoing environmental impact reporting. For smaller entities or individual projects, these costs can be prohibitive.
3) Despite existing standards, there is always a risk that the project financed by a green bond fails to meet environmental expectations or that the issuer does not fulfill promises regarding the use of proceeds. The green bond market is highly sensitive to reputational issues, incidents of misconduct could deter investors. Greenwashing is already cited as a significant challenge in the sector. Transparent disclosure of project parameters is crucial. Should an issuer undermine trust, the entire market segment could be negatively affected.
4) While strict Taxonomy criteria have advantages, they may also pose a barrier, because not all hydrogen-related projects qualify, reducing the instrument's applicability. Projects that do not perfectly meet green criteria may be excluded from green-bond financing channels.
5) Bond issuances are subject to market conditions. In an environment of rising interest rates, debt costs have grown relative to the period of historically low rates. This could adversely affect the profitability of financing hydrogen projects via bonds. Bond market volatility can also deter issuers from proceeding with new issuances.

Opportunities

1) Global and European hydrogen targets translate into hundreds of billions of euros in required capital, creating a natural space for green-bond market expansion. Institutional investors controlling trillions of euros are eager for large, long-term, high-impact investments.
2) EU regulations such as the European Green Bond Standard will render green bonds more appealing and credible. Member States' governments can employ green bonds to advance their strategies. The intensifying political push for green investments encourages financial institutions to increase their holdings of green assets.

3) Every successful green bond issuance for hydrogen strengthens market confidence. As investors see that hydrogen project financing can deliver stable, predictable returns and genuine environmental impact, they may allocate even larger sums for future issuances.
4) Hydrogen projects often produce multiple benefits Hence, financing them through green bonds can attract investors focused on a wide array of sustainability priorities. The multi-dimensional advantages of hydrogen can serve as a marketing argument during issuance, expanding the base of potential bond buyers.

Threats

1. The European Court of Auditors has indicated that EU hydrogen targets may be overly optimistic. If project rollout proceeds more slowly than anticipated, investor confidence in the sector's growth could be undermined. In a worst-case scenario, if some infrastructure remains underutilized due to insufficient hydrogen demand, the expected revenue streams may not materialize.
2. Currently, hydrogen enjoys robust political support but changes in government priorities or controversies cannot be ruled out. A sudden regulatory shift or delays in implementing support mechanisms could alter the landscape. Hydrogen has become an arena of geopolitical competition, if competing programs attract capital and projects away from Europe, opportunities for green-bond financing in this field could diminish.
3. The bond market is affected by macroeconomic trends. In the event of a recession or financial crisis, investors may shun riskier assets. High inflation or rising interest rates could elevate the cost of debt service to the point of undermining the financial viability of hydrogen projects.
4. An additional hazard stems from changing social attitudes— should the public or environmental groups question the rationale for investing in hydrogen, some funds might choose not to finance these projects.

8. Summary

Green bonds have become a key tool in financing the energy transition in the European Union, with increasing application to hydrogen projects. By linking the world of finance with sustainability they offer mutual benefits. Issuers gain access to capital for strategically important, innovative investments, while investors gain opportunities to participate in projects that benefit the climate without sacrificing the financial appeal of standard bonds. The analysis presented here indicates that green bonds have already played a role in launching the first large hydrogen projects in Europe. Issuances such as Gasunie's bond for the hydrogen network or Air Liquide's bond for low-carbon hydrogen initiatives have served as precedents, paving the way for further undertakings. EU Member State governments also actively use this instrument, allocating a portion of sovereign green-bond proceeds to hydrogen-related expenditures. This has led to the creation of an ecosystem in Europe that allows hydrogen projects to be funded transparently and sustainably.

- EU regulations further strengthen this market by providing uniform criteria and trust. As a result, investors can more confidently invest in hydrogen-labeled bonds, confident that the underlying projects meet rigorous environmental standards.
- The prospects for financing hydrogen through green bonds are promising, though realization of this potential will depend on several factors. First, on the successful deployment of key hydrogen projects. Second, on stable and consistent public policy, sustained support for hydrogen will reduce investment risk and draw more investors. Third, on efficient management of the inherent risks. Should these conditions be met, green bonds could become a cornerstone of financing the EU's hydrogen economy well into the 2030s and 2040s.
- It is noteworthy that green bonds are not a standalone solution, they should complement other sources of funding. Public grants, corporate equity and bank loans will play essential roles in assembling the financing for expensive hydrogen ventures. However, green bonds have a unique capacity to mobilize capital quickly and on a large scale.

In conclusion, experiences from past issuances and trend analyses suggest that green bonds have all the prerequisites to become a permanent and significant instrument in financing hydrogen projects in the EU. Their formal structure, regulatory backing and expanding investor base make them a credible, efficient way of raising funds for hydrogen ventures.

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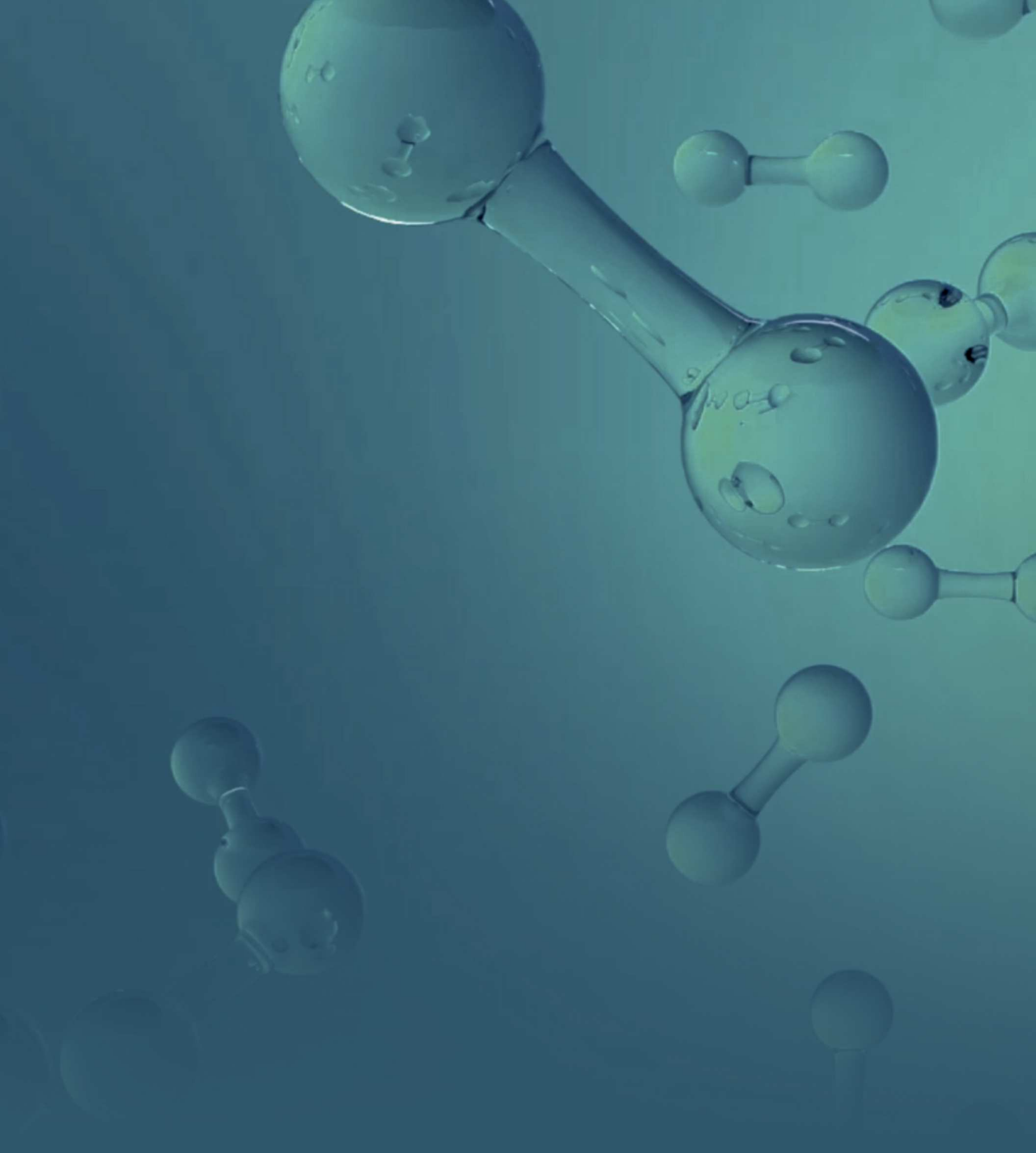
WYKORZYSTANIE ZIELONYCH OBLIGACJI W FINANSOWANIU PROJEKTÓW WODOROWYCH W UNII EUROPEJSKIEJ

Streszczenie

Rozdział analizuje wykorzystanie zielonych obligacji jako instrumentu finansowania projektów wodorowych w Unii Europejskiej, która dąży do osiągnięcia neutralności klimatycznej do 2050 roku. Wodór, zwłaszcza zielony wodór produkowany z odnawialnych źródeł energii, jest kluczowy dla dekarbonizacji trudnych sektorów gospodarki. Jednak rozwój infrastruktury wodorowej wymaga ogromnych nakładów finansowych, znacznie przekraczających możliwości funduszy publicznych. Zielone obligacje, których środki muszą być przeznaczone na cele środowiskowe, umożliwiają mobilizację kapitału prywatnego. UE i jej państwa członkowskie w tym Niemcy, Francja, Holandia i Polska aktywnie rozwijają ten rynek. Przykłady emisji, jak Gasunie czy Air Liquide, pokazują rosnące zainteresowanie inwestorów finansowaniem wodoru. W rozdziale zawarto analizę SWOT wskazującą na mocne strony (np. długoterminowe finansowanie, pozytywny wizerunek), słabości (np. koszty emisji, niepewność projektów), szanse (np. wysokie zapotrzebowanie inwestycyjne, wsparcie regulacyjne) i zagrożenia (np. zmienność rynków, ryzyko polityczne). Wnioski wskazują, że zielone obligacje mogą stać się filarem finansowania gospodarki wodorowej w UE. Choć nie zastąpią innych źródeł, ich rola będzie rosnąć wraz z dojrzewaniem projektów i rozwojem rynku zielonego finansowania.

Słowa kluczowe: wodór, zrównoważone finansowanie, gospodarka niskoemisyjna, transformacja energetyczna, polityka klimatyczna



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