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Hydrogen Vehicle Adoption: Perceptions, Barriers, and Global Strategies

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Abstract

This paper analyzes the potential of hydrogen technologies in transport, placing it within the context of global environmental and energy challenges. Its primary purpose is to evaluate the prospects for the implementation of these technologies at international and national levels, including Poland. This study utilizes a literature review and an analysis of the results of a highly limited, exploratory pilot survey measuring public perception of hydrogen technology in transport. It is critical to note that the survey was conducted on a small, non-representative sample and exhibited a strong geographical bias, primarily collecting responses from Europe (50 people) and North America (30 people). This study also details hydrogen vehicle types (FCEV, HICE) and the essential infrastructure required (HRS). Despite solid technological foundations, the development of hydrogen technology heavily relies on non-technical factors, such as infrastructure development, support policy, and social acceptance. Globally, the number of vehicles and stations is growing but remains limited, with the pace of development correlating with the involvement of countries. The pilot survey revealed a generally positive perception of the technology (mainly due to environmental benefits) but highlighted three key barriers: limited availability of refueling infrastructure—51.5% of respondents strongly agreed on this obstacle, high purchase and maintenance costs, and insufficient public awareness. Infrastructure subsidies and tax breaks were identified as effective incentives. Hydrogen technology offers a potentially competitive and sustainable transport solution, but it demands significant systemic support, intensive investment in large-scale infrastructure expansion, and comprehensive educational activities. Further governmental engagement is crucial. The severe limitations resulting from the pilot nature of the survey should be rigorously taken into account during interpretation.

Keywords: hydrogen; fuel cells; hydrogen vehicles; alternative drives; sustainable transport; hydrogen infrastructure; competitiveness; dynamic global changes

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1. Introduction

In the face of ongoing climate change, dwindling fossil fuel resources, and increasing pressure to reduce greenhouse gas emissions, hydrogen is gaining importance as an alternative, clean energy source. Its use in transportation could play a key role in the energy transition and decarbonization of the automotive sector. Hydrogen fuel cells are a promising technology that could significantly impact the vehicle market of the future, despite numerous challenges.

The purpose of the article is to present and analyze hydrogen as an energy source and assess the importance and extent of hydrogen technology development in transportation at the global, European, and national levels, including Poland. The focus is on the technical aspects of vehicles, the necessary infrastructure, as well as market and implementation considerations. An important element was the author's survey, a poll of opinions on hydrogen transportation among an international group of respondents. Special attention was paid to the potential users' perceptions of the technology, their concerns, and the barriers affecting interest in hydrogen vehicles. Also, the research objectives include quantifying key non-technical barriers, like limited public awareness and infrastructure, as a means toward addressing the identified research gaps and charting the future directions.

It was hypothesized that hydrogen technology, although in the development stage, has sufficient technological and conceptual foundations for dynamic development and is a viable competitor to traditional fossil fuel-based transportation in the coming years. At the same time, it was assumed that potential users may exhibit some distrust and apprehension, mainly due to limited refueling infrastructure, high purchase costs, and insufficient knowledge.

The motivation for choosing the topic was the growing presence of hydrogen in the energy and transportation strategies of many countries and the dynamic development of hydrogen-based technologies as an alternative to the dominant fuels. Public interest, increases in research and development, and support from international institutions make the topic timely.

Extensive literature covers the technological maturity of FCEVs (fuel cell electric vehicles) and HICEs (hydrogen internal combustion engines) and the policy frameworks supporting hydrogen (e.g., the EU Hydrogen Strategy, national plans like Poland's). While the technology is ready, research has historically overlooked or under-quantified the role of non-technical barriers (e.g., social, economic, and infrastructure readiness as perceived by the public). The existing studies concentrate on the high cost of hydrogen and the lack of infrastructure. Most of them address this issue from a developer/investor perspective (e.g., cost per station, return on investment, etc.). There is a gap in quantifying the consumer-side impact of these factors, i.e., how limited infrastructure directly translates into perceived range anxiety and how higher fuel/vehicle costs affect purchase willingness across different international markets. Also, there is a limited breadth in the literature concerning consumer attitude. It should be emphasized that the literature lacks a recent, targeted, and comparative quantitative survey that simultaneously measures three interconnected factors critical for adoption: public awareness (basic knowledge of the technology), perceived barriers (infrastructure and cost concerns), and acceptance/willingness (likelihood to purchase). Therefore, the novel contribution of this paper is the application of a pilot survey to quantify the severity of these non-technical adoption barriers from the consumer's perspective, specifically focusing on the relationship between public awareness and perception of cost/infrastructure in the context of global hydrogen strategies.

2. Perspectives and Development Trends of Hydrogen Vehicles and Infrastructure

Hydrogen, as a clean and sustainable energy carrier, has applications in many sectors. It is a key component of the energy transition. There are four stages in the hydrogen economy: production, transformation, transportation, and end use. Technological advances and investments in storage and transportation infrastructure are key to scaling hydrogen production and widespread use. In the future, hydrogen could become a new strategic commodity traded internationally, creating economic opportunities for RES-rich countries [1–4].

The ways to produce hydrogen are diverse, and one of the key challenges is efficient storage and transportation. Hydrogen can be transported in a gaseous state (compressed in cylinders or on pipe trailers for short to medium distances) or in a liquid state (cooled to −253 °C). There are also methods for storing hydrogen in underground reservoirs, offering high capacity and low environmental impact, although limited by geological formations and potentially expensive. Storage technologies also include the use of metal hydrides, which allow the hydrogen to be safely and efficiently stored in a solid form. Hydrogen storage disks, developed by French researchers using metal hydrides (especially magnesium), offer a safe, stable, and long-lasting solution, requiring less energy to store and release hydrogen than traditional methods. They are characterized by high stability, fire resistance, and no loss of hydrogen over time [5–7].

The term "hydrogen vehicles" covers various types of hydrogen-powered cars. There are two main ways to use hydrogen energy in vehicles: the use of fuel cells (they generate electricity) and direct combustion of hydrogen in an internal combustion engine (HICE). Like gasoline stations, there are hydrogen stations for refueling vehicles. Building hydrogen vehicles is technologically and economically challenging, and hydrogen, as a flammable gas, requires special attention in regard to storage and handling [8–11].

Fuel cell electric vehicles (FCEVs) represent an innovative propulsion solution, using hydrogen to generate electricity to drive an engine. Fleets of vehicles, such as city buses and courier companies, were early adopters of this technology, proving its functionality in real-world conditions. A comparative analysis of different propulsion systems (internal combustion, battery electric—BEV, FCEV) indicates that fuel cell hydrogen vehicles achieved the longest range and best top speed, with refueling taking only a few minutes [12,13].

The concept of HICE vehicles has a history of more than two hundred years. Interest in hydrogen as a fuel was revived during energy crises. A key figure in the development of hydrogen engines in the 1920s and 1930s was Rudolf Erren, who modified gasoline and diesel engines. Today's HICE vehicles use an internal combustion engine adapted to run on hydrogen. HICE have lower efficiency than fuel cells, especially at low load, due to the rapid combustion of hydrogen leading to high heat loss. Fuel cells achieve the highest efficiency at low load, and their performance approaches that of internal combustion engines as the load increases. Despite the high cost of fuel cells, HICE technology continues to play a key role in the research into the application of hydrogen in automobiles [14–17].

Examples of hydrogen vehicles include: Toyota Mirai (an advanced FCEV), Hyundai NEXO (a fuel-cell SUV), Mercedes-Benz GLC F-CELL (a fuel-cell plug-in hybrid), BMW Hydrogen 7 (an experimental hydrogen-powered sedan), and BMW iX5 Hydrogen (a modern hydrogen-powered SUV, mainly for testing and fleet purposes) [18–24]. NesoBus hydrogen buses, manufactured in Świdnik, are coming to the Polish market. Tests of NesoBuses have been carried out in major urban centers, indicating a growing interest in the technology nationally [25,26].

The performance and cost-effectiveness of hydrogen vehicles are analyzed in studies that evaluated fuel consumption, durability, efficiency, range and operating costs. A variety of energy management strategies are being applied to fuel cell vehicles, such as peak power source strategy, mode control strategy, and fuzzy logic control strategy [27–30]. These strategies make optimal use of the fuel cell, supercapacitors, and batteries, increasing the smoothness and energy efficiency of the powertrain [31–33]. Studies indicate that FCEVs can have significantly higher operating costs than battery electric vehicles (BEVs) and internal combustion engine vehicles (ICEVs), mainly due to hydrogen and infrastructure costs. However, in some applications, such as heavy-duty vehicles, fuel cells can save money compared to diesel vehicles [34–37]. The cost-effectiveness of HFC technology depends on the cost of hydrogen production and fuel cell technology. Mass production, ef-

ficient energy management, and government support (such as subsidies, tax breaks) are key to making HFCs competitive.

FCEVs report lower-life-cycle greenhouse gas emissions than conventional internal combustion vehicles when hydrogen is produced from renewable sources. For example, studies using well-to-wheels assessments [38] show FCEV emissions can be 15–72% lower than those of ICEVs, provided that electrolysis or other low-carbon pathways are used. In contrast, one study on hydrogen internal combustion engine vehicles (HICEVs) found that about 30 kilowatt-hours per 100 km are required for these vehicles to be competitive with battery electric vehicles [39].

In terms of energy utilization efficiency, FCEVs use 5–33% less fossil energy than ICEVs [40] but generally require more fuel input than BEVs—a disparity also noted by Miotti et al. (2017) [41] when comparing tank-to-wheel efficiency. The performance of both technologies is sensitive to the hydrogen production method; SMR without carbon capture yields limited benefits, while renewable or nuclear pathways result in marked improvements.

Studies addressing hydrogen vehicle adoption report that high vehicle and component costs, infrastructure gaps, and policy constraints limit market penetration [40–46]. Regional factors further shape outcomes: FCEVs in the United States perform well even with SMR hydrogen; in Europe and other regions, benefits from hydrogen vehicle adoption depend strongly on the prevailing grid mix and supportive policy frameworks.

Regional or international studies highlight the importance of grid mix and/or policy context in determining the relative benefits of fuel cell electric vehicles, battery electric vehicles, and internal combustion engines or fuel cell vehicles. The competitiveness of hydrogen-based vehicles is highly dependent on regional energy sources and policy frameworks [47,48].

In fact, the development of hydrogen infrastructure is a key component of global energy strategies. In Europe, there is an emphasis on developing green hydrogen from RES. High-capacity electrolyzers are being built, and countries are implementing strategies to support low-carbon hydrogen production. Efficient storage and transportation of hydrogen remain a challenge; hydrogen can be stored as compressed gas, liquid, or in chemical compounds. Dedicated hydrogen pipelines are being developed, such as the planned European Hydrogen Backbone network. Hydrogen refueling standards (e.g., 700 bar for cars, 350 bar for trucks) are key to the development of Hydrogen Refueling Stations (HRS). Appropriate energy management strategies at stations can help reduce operating costs [49,50].

There are more than 920 hydrogen refueling stations worldwide (See Figure 1), with a majority situated in Asia (525) and Europe (265) [51,52]. The leaders, in terms of the number of stations in Europe, are Germany (105), France (25), and the Netherlands (22). Poland has seven publicly available hydrogen stations, including those under the NESO brand (Warsaw, Gdansk, Gdynia, Lublin, Rybnik) and the ORLEN Group (Poznan, Katowice). NESO stations serve different types of vehicles with different refueling pressures (700 bar for passenger cars, 350 bar for trucks/buses), with refueling times of several minutes or more [51]. The number of hydrogen vehicles worldwide is growing, although the efficiency of the development of refueling infrastructure has had a key impact on their availability. As of early 2024, about 78,000 hydrogen vehicles had been registered globally, most of which were passenger cars (88.5%). Global sales of hydrogen cars decreased 30.2% in 2023, with notable declines in sales of Hyundai and Toyota models [44,45].

The data in Figure 2 show that passenger cars make up the largest segment in the global fleet of hydrogen vehicles (FCVs), accounting for 75% of the total. This means that for every four registered hydrogen vehicles, three are passenger cars. The next largest group is buses, which account for 9% of the FCV fleet, followed by heavy trucks with a

share of 8% and medium trucks with 5%. Light commercial vehicles account for only 3%, which is a much smaller share [53].

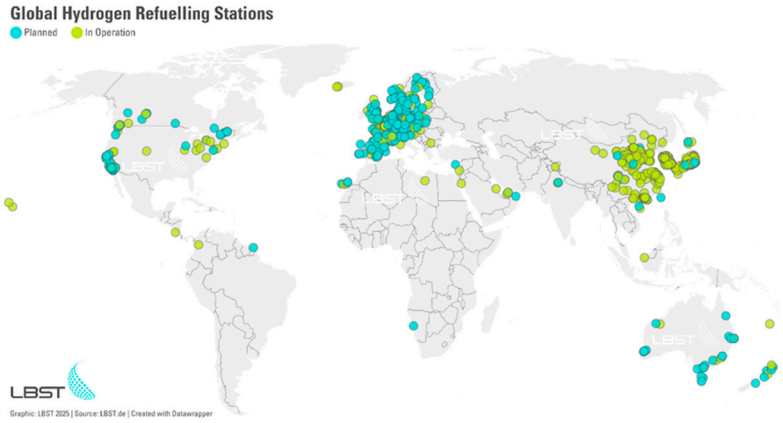


Figure 1. Map of hydrogen refueling stations around the world. Source: [52].

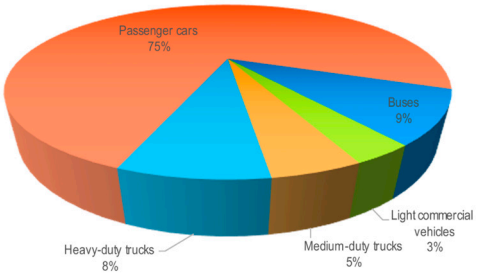


Figure 2. Breakdown by category of hydrogen vehicles in 2023. Source: [53].

Governments, international organizations, and the private sector support the development of hydrogen technology and infrastructure, recognizing hydrogen's importance in future energy [54–57]. National strategies are tailored to local needs, including subsidies, R&D support, pilot programs, and the construction of refueling stations. Global leaders, primarily in Asia (Japan, China, and South Korea), have implemented comprehensive long-term plans aimed at making hydrogen a primary energy carrier by 2050 (Japan) and focusing on green hydrogen production, transportation ecosystems (buses, trucks), and technological deployment. For instance, South Korea has promoted the "Korea Hydrogen Economy" with an emphasis on fuel cell public transportation. The European Union supports its strategy to achieve climate neutrality through programs like IPCEI Hydrogen. Similarly, the US utilizes strategies, like the Road Map to a US Hydrogen Economy, with localized promotion through tax credits (e.g., California). Other countries, including India, Chile, and Australia, have also established national strategies focused on developing green hydrogen and related infrastructure, such as "The Hydrogen Highway".

The Polish Hydrogen Strategy (PSW) set for 2030, with an outlook to 2040, specifically aims to create a Polish branch of the hydrogen economy based on national potential. The key objectives of the PSW include the implementation of hydrogen technologies in power and heating, the use of hydrogen in transport and industry, the development of low-carbon production, and the construction of essential distribution and storage infrastructure. These global and national initiatives (see Appendix A for details) highlight the universal focus on production, storage, applications, and infrastructure expansion [58–71].

3. Materials and Methods

The research methods included a literature review and systematic analysis (academic articles, industry reports, policy documents) and a pilot survey using a questionnaire de-

veloped in English and made available on the SurveySwap platform. The survey was designed to gather the opinions and concerns of potential consumers toward hydrogen technology in transportation. The data was subjected to statistical analysis. This allowed us to identify the current state of knowledge about hydrogen technologies, market trends, and implementation challenges, taking into account scientific articles (from Scopus databases, Web of Science), industry reports (e.g., IEA, Hydrogen Council), as well as strategic documents (UN, EU, or national).

In addition, a pilot research survey was carried out in which a questionnaire tool was used (see Appendix B). The aim of the survey was to find out the public's opinion on the development of hydrogen technology in transportation and to identify factors influencing the acceptance of this propulsion system among potential users. The survey also aimed to verify the extent to which the public perceives hydrogen as an alternative to internal combustion vehicles, and what psychological, economic, and infrastructural barriers affect consumer decisions. Analysis of the opinions of an international group of respondents was intended to help understand perceptions of the technology and the specifics of regional challenges.

The survey was international, targeting a wide range of respondents without restrictions. A questionnaire in English was prepared in Google Forms and made available on the SurveySwap platform. The questionnaire consisted of 11 closed-ended questions (single-choice, Likert scale) on the knowledge of the technology, acceptable price, benefits, barriers, and expectations of government incentives.

A pilot version of the survey was conducted, the purpose of which was to check the comprehensibility of the questions, the functionality of the form, and the correctness of the logic circuit. The pilot did not reveal any errors or irregularities, so the study continued unchanged using the pilot as the actual survey.

Data collection lasted from 17 November 2024 to 21 January 2025. Of those surveyed, 107 people participated, of which 103 correctly completed questionnaires were qualified. Four answers were rejected due to the answers in the open question that did not comply with the instructions. The structure of the survey made it possible to collect both demographic data and the opinions and attitudes of the respondents.

Respondents were predominantly from Europe (50 people), followed by North America (30) and Asia (18). The largest number of responses came from the US (27), the UK (17), the Netherlands (12), and Germany (11). The data collected were analyzed using statistical methods, which allowed for their objective interpretation. Non-parametric tests were chosen due to the ordinal nature of all variables in the study (Likert scale). In the case of examining the influence of gender, the Mann–Whitney U test was used, and in the case of age and continent, the non-parametric Kruskal–Wallis ANOVA test was used. Both tests, in their null hypothesis, assume equality of medians (average values) of responses across all groups, while in alternative hypotheses, they assume statistically significant differences between medians. In all statistical tests used in the analysis, a significance level of $\alpha = 0.05$ was adopted. The assumptions of both tests are that the data are at least ordinal and that the samples are independent. The advantage, on the other hand, is that the assumption of normality of distributions need not be met. In the study, both assumptions of the Mann–Whitney U test and the Kruskal–Wallis H test were met. The tests also required a relatively large sample size. This assumption was met and the sample size should not significantly affect the outcome of the tests.

The results of the survey, due to its pilot nature and methodological limitations (time, survey sample composition), are not representative of the population of individual countries. The vast majority of participants came from countries where hydrogen infrastructure is developing poorly or is at an early stage. There was a lack of significant representation

of people from countries that are leaders in hydrogen transportation (e.g., South Korea, Japan, China), where residents have more contact with the technology and a higher level of awareness. The results obtained may be limited in its reflection the overall attitude towards hydrogen technology, as those surveyed were from countries with poorly developed or early stage hydrogen infrastructure. In the future, it would be worthwhile to expand the research methodologically (qualitative methods, interviews with experts) and geographically (balanced selection of respondents from countries with different levels of advancement) to obtain more detailed opinions and representative analysis.

4. Results

The self-assessment of one's knowledge of hydrogen technologies in transportation showed a low level of awareness: the largest group (33%) declared little knowledge, and 27.2% admitted to having no knowledge. Medium knowledge was declared by 19.4%, good knowledge by 16.5%, and very good knowledge by only 3.9%. The acceptable price range for purchasing a hydrogen vehicle was most often indicated to be below $30,000 (33%), with 28.2% for the $30,000–$40,000 range, and 24.3% for the $40,000–$50,000 range.

The highest rated factors considered important in evaluating alternative power sources (scale of 1–5) were availability and convenience of use (mean: 4.2) and purchase and operating costs (mean: 4.1). Environmental impact and emissions received a mean score of 4.0 (See Table 1).

Table 1. Factors important in evaluating alternative power sources.

Answers	Total					Average
	Definitely Not Relevant 1	Rather Irrelevant 2	Partly Relevant 3	Rather Relevant 4	Definitely Relevant 5	
	%	%	%	%	%	
Environmental impact and low emissions	3.9	6.8	13.6	34.0	41.7	4.0
Accessibility and convenience of use	1.0	6.8	11.7	35.0	45.6	4.2
Vehicle purchase and operating costs	1.0	5.8	16.5	34.0	42.7	4.1
Potential to support new technologies in transportation	3.9	16.5	25.2	35.0	19.4	3.5
Independence from traditional fossil fuels	1.9	10.7	22.3	35.9	29.1	3.8

Source: own research.

In the study, participants also assessed the extent to which they agreed with selected barriers to the development of hydrogen vehicle technology. The highest rated barrier was the lack of adequate refueling infrastructure (average 4.2), with 51.5% of respondents strongly agreeing. Other significant barriers were limited public awareness (average 4.0) and high production and maintenance costs (average 3.9). Low model availability and lack of government incentives (both mean 3.7) were also seen as significant, though less pressing (See Table 2).

Of the potential advantages of developing hydrogen vehicles (scale of 1–5), the highest rated were the reduction in urban air pollution (mean 4.2) and independence from oil price fluctuations (mean 4.0) were also considered important (See Table 3).

Table 2. Barriers to the development of hydrogen vehicles.

Answers	Total					Average
	Definitely Not Relevant 1	Rather Irrelevant 2	Partly Relevant 3	Rather Relevant 4	Definitely Relevant 5	
	%	%	%	%	%	
High production and maintenance costs	3.9	6.8	17.5	35.0	36.9	3.9
Lack of sufficient refueling infrastructure	0.0	6.8	16.5	25.2	51.5	4.2
Low availability of hydrogen vehicle models on the market	1.9	10.7	28.2	30.1	29.1	3.7
Insufficient government incentives or tax breaks	1	14.6	24.3	36.9	23.3	3.7
Limited public awareness of hydrogen vehicles	1.9	8.7	20.4	36.2	42.7	4

Source: own research.

Table 3. Potential advantages of developing hydrogen vehicles.

Answers	Total					Average
	Definitely Not Relevant 1	Rather Irrelevant 2	Partly Relevant 3	Rather Relevant 4	Definitely Relevant 5	
	%	%	%	%	%	
Reduction in greenhouse gas emissions	1.9	3.9	15.5	43.7	35.0	3.9
Noise reduction in urban areas	1.0	12.6	29.1	41.7	15.5	4.2
Support for sustainable energy development	0.0	3.9	23.3	47.6	25.2	3.7
Creating new jobs in alternative technology sectors	0.0	7.8	29.1	48.5	14.6	3.7
Independence from fluctuations in international oil prices	1.0	6.8	29.1	36.9	26.2	4

Source: own research.

Among the motivations for considering the purchase of a hydrogen vehicle (scale of 1–5), the highest averages were low emissions and impact on public health (mean 4.1) and environmental protection and reduction in personal carbon footprint (mean 3.9). The desire to own a modern vehicle had a lower average (3.1) (See Table 4).

The effectiveness of various government incentives (scale of 1–5) was rated relatively high: infrastructure grants (average of 3.9) and purchase tax credits (average of 3.9). Vehicle replacement programs received an average of 3.8, and 3.7 for insurance premiums. Leasing programs had the lowest average (3.6) (See Table 5).

The assessment of the perceived probability of implementing hydrogen technology in transportation in the respondent's country of residence varied, with most people (34%) indicating a medium chance, 30.1% a low chance, and 22.3% a high chance.

Table 4. Motivations for considering the purchase of a hydrogen vehicle.

Answers	Total					Average
	Definitely Not Relevant 1	Rather Irrelevant 2	Partly Relevant 3	Rather Relevant 4	Definitely Relevant 5	
	%	%	%	%	%	
Protecting the environment and reducing your personal carbon footprint	3.9	4.9	17.5	44.7	29.1	3.9
Willingness to own a modern, innovative vehicle	6.8	25.2	35.0	22.3	10.7	3.1
Potential tax credits and financial incentives	5.8	9.7	31.1	36.9	16.5	3.5
Independence from fossil fuel price fluctuations	1.0	11.7	29.1	28.2	30.1	3.8
Low emissions and impact on public health	1.0	2.9	15.5	47.6	33.0	4.1

Source: own research.

Table 5. Effectiveness of government incentives.

Answers	Total					Average
	Definitely Not Relevant 1	Rather Irrelevant 2	Partly Relevant 3	Rather Relevant 4	Definitely Relevant 5	
	%	%	%	%	%	
Tax credits for purchasing hydrogen vehicles	4.9	4.9	20.4	36.9	33.0	3.9
Programs to replace older vehicles with new, environmentally friendly ones	1.9	9.7	24.3	31.1	33.0	3.8
Subsidies for installation of hydrogen infrastructure	1.0	5.8	25.2	42.7	25.2	3.9
Leasing programs with favorable financial terms	1.9	15.5	27.2	35.9	19.4	3.6
Insurance premiums for owners of alternative fuel vehicles	1.9	10.7	24.3	39.8	23.3	3.7

Source: own research.

5. Discussion

From the perspective of this study, it may be important to identify factors that significantly differentiated respondents' answers to the questions asked (see Appendices B and C). Such potential factors include gender, age, and the continent of origin of the respondent (country of origin cannot be taken into account in this analysis due to too many different countries and, consequently, too few respondents from individual countries). The significance of the influence of these factors on the answers was investigated using non-parametric significance tests applied to all the questions. The question "Does the factor differentiate respondents' answers to the question?" was answered.

As a result of the analysis, it was found that gender significantly differentiated responses to only three questions: 4, 7.3, and 9.4. The results of the analysis are presented

in Table 6. In Question 4, respondents were asked to assess their knowledge of hydrogen technologies in automobiles. On average, respondents rated their knowledge in this area as low. When divided by gender, it was found that men rated their knowledge higher than women. Men rated it as average, while women rated it as low.

Table 6. Statistically significant results of the Mann–Whitney U test (test statistic *U* and *z*, significance *p*) of the influence of gender on responses and quartile values of responses.

	Statistics				Q1	Me	Q3
	U	***Z***	***p***				
Question 4	877	−3.206	0.001	F	1	2	3
				M	2	3	4
Question 7.3	1062	1.971	0.049	F	3	4	5
				M	3	3	4
Question 9.4	1001	2.389	0.017	F	3	4	5
				M	3	3.5	4

In response to Question 7.3, concerning the assessment of how significant a barrier was to the introduction of hydrogen technology, in the case of the poor availability of hydrogen-powered cars on the market, the average respondent stated that they partially agreed with this statement. When divided by gender, men agreed with this statement more often than women.

For Question 9.4, concerning motivations for purchasing a hydrogen-powered vehicle, on average, respondents tended to agree with the independence from changes in (traditional) fuel prices on the market as a motivating factor. However, women disagreed with this statement more often than men.

In the case of age, the results demonstrated that this factor did not significantly differentiate any of the questions. It can therefore be stated that, regardless of age, respondents gave similar answers.

The last factor examined was the continent of origin of the respondent. After performing K–W tests for all questions, it was found that significant differences were detected in responses to Questions 6.2, 7.4, 7.5, 9.4. The results are presented in Table 7. The medians of the responses to all four questions for the overall respondents indicated that they were inclined to agree with the statements in the questions. However, significant differences could be observed when dividing respondents by continent. Question 6.2 concerned the availability and convenience of using hydrogen as an important factor in the assessment of alternative energy sources. The results demonstrated that, in Africa and Australia and Oceania, this factor was considered very important, while in America and Asia, this factor was considered quite significant. Perhaps the availability of hydrogen sources on the continent influenced the responses.

Questions 7.4 and 7.5 concerned barriers to the development of hydrogen technologies in automotive. In Question 7.4, the barrier indicated was insufficient government incentives and tax breaks. Respondents from Africa strongly agreed with this statement, while respondents from Asia and America most often partially agreed. Question 7.5 indicated limited public awareness as the barrier to development. Respondents from Africa, America, and Australia and Oceania strongly agreed with the statement, while respondents from Europe and Asia rather agreed.

In Statement 9.4, the motivation indicated for considering the purchase of hydrogen technology was independence from changes in fuel prices. Respondents from Africa strongly

agreed with this statement, while respondents from Asia partially agreed. In other cases, the respondent's origin did not differentiate their approach to the questions/statements.

Table 7. Statistically significant results of the Kruskal–Wallis test (test statistic and significance) of the influence of continent on the differentiation of respondents' answers and response medians.

	Question			
	6.2	**7.4**	**7.5**	**9.4**
	K–W test			
H statistic	10.664	12.129	13.206	10.929
Significance *p*	0.031	0.016	0.010	0.027
	Median			
Total	4	4	4	4
Africa	5	5	5	5
America	4	3.5	5	4
Australia and Oceania	5	4	5	4
Asia	4	3	4	3
Europe	4.5	4	4	4

It is of interest to examine whether respondents' declared knowledge influenced the answers given in the survey. For this purpose, due to the ordinal nature of the data, Spearman's rank correlation was used along with a significance test for the correlation coefficient. In the vast majority of cases, respondents' knowledge was not significantly related to their answers to the questions. The exceptions were statements negatively correlated with knowledge (the more knowledge, the less often they agreed with the statement), and such statements were:

- the cost of hydrogen technology influences its evaluation,
- limited public awareness is a barrier to development,
- independence from changes in fuel prices as a motivation for engaging in hydrogen technologies,
- programs for exchanging old cars for new, alternatively powered ones, as government incentives for engaging in alternative automobiles.

A positive correlation was also noted between the respondents' knowledge of hydrogen technologies in automobiles and their belief in the possibility of implementing hydrogen-powered vehicle technology within the next decade. People with greater knowledge were more likely to believe in such a possibility.

The survey was exploratory and pilot in nature. Most respondents had a general, often superficial, knowledge of hydrogen vehicles, suggesting the need for broader information campaigns to increase confidence and understanding of the technology. Despite information gaps, most respondents saw hydrogen as the fuel of the future due to its environmentally friendly nature. The most frequently cited major barrier to widespread deployment is the limited availability of refueling stations, particularly emphasized by those from countries with early hydrogen infrastructure development. The cost of purchasing vehicles was also seen as a significant obstacle, despite perceptions of long-term operational benefits. Concerns included affordability and lack of sufficient financial support.

Finally, the survey, despite its limitations, provided an exploratory quantitative snapshot of consumer perceptions in regions undergoing early stage hydrogen adoption. The barriers identified, cost and infrastructure, are precisely the areas where global leaders (Japan, Korea, China) have deployed their most aggressive systemic and financial support, thereby validating the strategic necessities for FCEV competitiveness internationally. Fu-

ture research is necessary to expand the methodological and geographical scope, ensuring a balanced selection of respondents from countries with different levels of advancement, including leaders in this technology from Asia, to provide a more detailed and representative global analysis.

6. Conclusions

Hydrogen technology has gained prominence as a viable alternative to fossil fuels in the context of transportation decarbonization. The analysis confirms that hydrogen has a solid technological foundation, and its further development depends on non-technical factors such as infrastructure, supportive policies, and the level of public acceptance. The pace of development of hydrogen vehicles and refueling stations is gradually increasing, although their number worldwide, as in Poland, is still relatively small. The largest FCEV markets are South Korea, China, the US, and Japan; in Europe, Germany is the leader. Infrastructure development and vehicle availability are strongly correlated with state involvement and support policies.

Crucial to this study, the following findings are drawn from a limited, exploratory pilot survey and are not representative of the global population. The survey involved only 103 qualified respondents and suffered from a strong geographical bias, predominantly reflecting the perspectives of countries where hydrogen infrastructure is developing poorly or is at an early stage (mainly Europe and North America). The lack of significant representation from countries that are leaders in hydrogen transportation (e.g., South Korea, Japan, and China) fundamentally restricts the generalizability of these results. Despite these methodological constraints, the results from the limited sample suggest that hydrogen technology is viewed positively, especially in terms of environmental benefits. However, it also highlighted specific barriers: high costs, limited availability of refueling infrastructure, and lack of public knowledge.

Therefore, the findings are indicative, not conclusive; they support the hypothesis that hydrogen technology has the potential to develop rapidly and become a competitive solution to traditional transportation, provided that certain conditions for systemic, infrastructural, and social development are met. Further government involvement, investment support, and international cooperation are key issues. These conclusions should be interpreted strictly in the context of the surveyed group and serve as preliminary data for guiding future, methodologically balanced research.

The gaps to be addressed, suggesting the path forward for the field are the following:

(1) Future efforts must shift from purely technical optimization to socio-economic readiness.
(2) Future policy must prioritize targeted educational campaigns to overcome low public awareness.
(3) Future investment must focus on HRS expansion to mitigate perceived range/refueling anxiety, as this is a quantifiable bottleneck to consumer adoption.

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Abbreviation

Abbreviation	Explanation	Context
F	Female respondents	Demographic group
M	Male respondents	Demographic group
Q1	First Quartile (25th percentile of responses)	Data position
Me	Median (50th percentile of responses, the central value)	Data position (used for non-parametric comparison)
Q3	Third Quartile (75th percentile of responses)	Data position
U	Mann–Whitney U test statistic	Test statistic
z	Normalized test statistic	Test statistic (used for large-sample approximation of U test)
p	Significance value (p-value)	Statistical significance (tested against alpha = 0.05)
K–W test	Kruskal–Wallis ANOVA test	Non-parametric test for comparing three or more groups
H statistic	Kruskal–Wallis H test statistic	Test statistic
Significance p	Significance value (p-value)	Statistical significance (tested against alpha = 0.05)
Median (Total)	Median of responses for the entire sample (N = 103)	Overall central value
Median (Continent)	Median of responses for the specific continental subgroup (e.g., Africa, America)	Subgroup central value

Appendix A

Examples of domestic initiatives:

1. Japan: The Hydrogen Basic Strategy with the goal of making hydrogen the primary energy carrier by 2050, including infrastructure development, transportation support, and investment in manufacturing (e.g., FH2R), supported by the Green Innovation Fund.
2. China: The Hydrogen Industry Development Plan (2021–2035) focusing on green hydrogen, hydrogen transportation ecosystem (buses, trucks), and hydrogen hubs, supported by China Hydrogen Alliance.
3. South Korea: The "Korea Hydrogen Economy" program with a focus on fuel cell public transportation and the deployment of storage/transfer technology, with a key role for Hyundai and cooperation with Korea Gas Corporation. The city of Ulsan is a model for integrating hydrogen into various areas of the economy.
4. India: The National Green Hydrogen Mission with a goal of producing five million tons of green hydrogen by 2030, including building RES-powered electrolyzers and working with industrial companies.
5. US: The Road Map to a US Hydrogen Economy strategy, with the example of California promoting hydrogen technology through tax credits and fuel surcharges, as well as dedicated lanes.

6. Chile: The National Green Hydrogen Strategy focusing on developing domestic demand and export market.
7. Australia: The National Hydrogen Strategy 2024 and initiatives such as "The Hydrogen Highway."
8. European Union: A European hydrogen strategy to achieve climate neutrality by 2050 and enhance energy security, supported by the IPCEI Hydrogen and Clean Hydrogen Partnership programs.
9. Poland: The Polish Hydrogen Strategy set for 2030 with an outlook to 2040 (PSW) adopted in 2021 to support decarbonization and strengthen competitiveness.

Appendix B

Research Survey: International Perceptions and Preferences for Hydrogen Vehicles

I kindly ask you to complete a survey questionnaire. The aim of the survey is to collect data on opinions about hydrogen vehicles. The results of the survey will be used as part of my Master's thesis at Gdynia Maritime University.

The survey is voluntary and anonymous. Survey time: approx. 7 min.

1. **Gender:**
   - Man
   - Woman
   - Prefer not to say
2. **Age:**
   - 18–24 years
   - 25–34 years
   - 35–44 years
   - 45–54 years
   - 55–64 years
   - 65 years and older
3. **Country of residence:**
4. **How would you rate your knowledge of hydrogen technology in transport?**
   - Very good
   - Good
   - Average
   - Low
   - No knowledge on this topic
5. **What price range would you consider acceptable for purchasing a hydrogen vehicle?**
   - Less than $30,000
   - $30,000–$40,000
   - $40,000–$50,000
   - $50,000–$60,000
   - More than $60,000
6. **What factors are important to you when evaluating alternative power sources, such as hydrogen? Please rate on a scale from 1 to 5, indicating how important each is:**

   1: Definitely not important
   2: Rather unimportant
   3: Partially important
   4: Rather important
   5: Definitely important

   - Environmental impact and low emissions

- Availability and convenience of use
- Vehicle purchase and operating costs
- Potential to support new technologies in transportation
- Independence from traditional fossil fuels

7. **To what extent do you consider the following issues as barriers to the development of hydrogen technology? Please rate on a scale from 1 to 5, indicating how effective each is:**

1: Strongly disagree
2: Somewhat disagree
3: Partially agree
4: Somewhat agree
5: Strongly agree

- High costs of hydrogen vehicle production and maintenance
- Lack of sufficient fueling infrastructure
- Low availability of hydrogen vehicle models on the market
- Insufficient government incentives or tax breaks
- Limited public awareness of hydrogen vehicles

8. **How would you rate the following potential benefits of developing hydrogen vehicles? Please rate on a scale from 1 to 5, indicating how effective each is:**

1: Strongly disagree
2: Somewhat disagree
3: Partially agree
4: Somewhat agree
5: Strongly agree

- Reduction in greenhouse gas emissions
- Noise reduction in urban areas
- Support for sustainable energy development
- Creation of new jobs in alternative technology sectors
- Independence from fluctuations in international oil prices

9. **What are your motivations for considering the purchase of a hydrogen vehicle? Please rate on a scale from 1 to 5, indicating how important each is:**

1: Definitely not important
2: Rather unimportant
3: Partially important
4: Rather important
5: Definitely important

- Environmental protection and reduction in personal carbon footprint
- Desire for a modern, innovative vehicle
- Potential tax breaks and financial incentives
- Independence from fossil fuel price fluctuations
- Low emissions and public health impact

10. **What types of government incentives would be most effective for you in purchasing an alternative-fuel vehicle? Please rate on a scale from 1 to 5, indicating how effective each is:**

1: Definitely ineffective
2: Rather ineffective
3: Partially effective
4: Rather effective

5: Definitely effective
   - Tax breaks for purchasing hydrogen vehicles
   - Programs to exchange older vehicles for new, eco-friendly ones
   - Grants for hydrogen infrastructure installation
   - Leasing programs with favorable financial terms
   - Insurance bonuses for owners of alternative-fuel vehicles

11. **How would you rate the possibility of implementing hydrogen technology in transport in your country in the next decade?**
   - Very high, there are many initiatives and investments
   - High, it is developing but needs support
   - Medium, there are obstacles to overcome
   - Low, major infrastructural and social change needed
   - Very low, no conditions for development

Appendix C

Tables 6 and 7 explanation and statistical detail clarification.

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