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HYDROGEN ENERGY AS A CATALYST FOR SUSTAINABLE DEVELOPMENT: A COMPARATIVE ANALYSIS OF POLICIES, STRATEGIES, AND IMPLEMENTATION IN POLAND AND GERMANY

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Purpose: The study aims to investigate the role of hydrogen technology in sustainable energy in Poland and Germany. It seeks to offer a comparative analysis to fill gaps in existing literature and provide insights for stakeholders in achieving Sustainable Development Goals.
Design/methodology/approach: A multifaceted approach is employed, integrating a literature review, tabular analysis, and surveys. Scientific publications, government reports, and research papers are analyzed. Tabular comparisons elucidate differences and similarities in strategies and regulations between the two countries. Surveys among social and professional groups capture public perception and attitudes.
Findings: Hydrogen technology has gained significant attention as a sustainable energy source. Germany emerges as a leader with a comprehensive strategy, while Poland aligns with EU objectives but faces infrastructure challenges. Both nations have introduced regulations to promote hydrogen technology investment, although challenges such as high production costs persist. Public support is robust in both countries, with higher awareness in Germany.
Research limitations/implications: The study's scope could be expanded for a more comprehensive understanding. Future research could focus on addressing these limitations and offering more granular insights.
Practical implications: The study serves as a roadmap for stakeholders, offering insights that can guide policy formulation and investment decisions. It has implications for climate change mitigation efforts and could inform public engagement campaigns.
Social implications: The study underscores hydrogen technology's potential in reducing greenhouse gas emissions and fostering economic growth, thereby impacting various societal aspects including environmental protection and economic development.
Originality/value: The study's uniqueness lies in its comparative analysis of hydrogen technology in Poland and Germany, contributing to the global discourse on sustainable development by offering practical insights for policymakers and industry leaders.

Keywords: Hydrogen energy, sustainable development, Poland, Germany, energy strategies, government policies, renewable energy, decarbonisation.

Category of the paper: research paper.

1. Introduction

Amidst the accelerating global shift toward sustainable energy, hydrogen technologies have garnered substantial attention as potential catalysts for achieving Sustainable Development Goals (SDGs). The original contribution of this study lies in its attempt to bridge an epistemological gap; while existing literature broadly investigates the technological facets of hydrogen as an energy carrier, scant attention has been paid to its multi-dimensional implications across economic, social, political, and environmental spheres. Consequently, this study aims to answer the question: How do hydrogen technologies align with, and potentially advance, the objectives of sustainable development in varying national contexts, specifically Poland and Germany? The principal objective of this article is to conduct a comparative analysis of hydrogen policies and their implications for sustainable development in Poland and Germany. To achieve this, the analysis will also elucidate key frameworks and theories that govern the adoption of hydrogen technologies, thereby providing a multi-dimensional perspective. It is hypothesized that the strategic adoption of hydrogen technologies will vary between Poland and Germany due to their respective economic, political, and cultural landscapes. To substantiate these objectives and hypotheses, a mixed-methods approach will be employed, encompassing both qualitative and quantitative data analysis.

In recent years, the hydrogen technology boom has gained importance as a key element in the global energy transformation, leading to increased interest in this element as a potential source of energy. The movement is part of a broader trend where new and sustainable technologies are becoming a key pillar in the pursuit of sustainable development around the world. The hydrogen tech boom is not random or isolated; it is related to the global understanding and recognition that conventional energy sources such as oil and coal are becoming less and less sustainable from both an economic and ecological point of view. The development of hydrogen technologies is part of the global movement towards ecology and sustainable development, which assumes that the future of the energy sector must be built on the principles of sustainable resource management. A comprehensive approach to analyzing the role of hydrogen in the pursuit of sustainable development is key. This means that hydrogen cannot be seen solely as a technological energy carrier; instead, it must be considered in political, economic, social and environmental contexts, as these aspects are interrelated and influence how hydrogen can be used to achieve the Sustainable Development Goals. It is important to combine theoretical and practical analysis of hydrogen energy in two different national contexts: Poland and Germany. While economically, politically and culturally different, these two countries are interesting cases to study as both are actively seeking to understand and exploit the potential of hydrogen as a key element of their energy strategies. It is essential to understand the broader context of hydrogen energy, exploring key concepts, theories and frameworks that can help explain why hydrogen has become such an important element in today's energy strategies.

Therefore, the theoretical analysis is not just limited to the technical and engineering aspects of hydrogen, but goes deeper, trying to understand how hydrogen fits into the larger sustainability narrative, what are its potential benefits and challenges, and how it can be put into practice in different national and international contexts, including Poland and Germany.

2. Development of Hydrogen Energy in Poland

The beginnings of hydrogen energy in Poland date back to the 1970s, when research on the use of hydrogen as an energy carrier began. Leading scientific institutes conducted experiments on the storage and transport of hydrogen and its use in fuel cells. In the 1990s, the first investments in hydrogen technology appeared (Spandagos, Reanos, Lynch, 2022).

The introduction of research and development initiatives enabled the implementation of several key projects related to the production of hydrogen from renewable energy sources. These early projects contributed to the development of expertise in the field of hydrogen technologies in Poland. Over the last two decades, hydrogen has started to play a more important role in the Polish energy mix. Hydrogen technologies are increasingly being considered as a key tool in the country's energy transformation, helping to decarbonise the energy sector. Hydrogen is used not only as an energy carrier but also in industry and transport (Jałowiec et al., 2022; Kochanek, 2022, pp. 72-73).

Currently, Poland is witnessing dynamic growth in the field of hydrogen energy. There are initiatives at both government and private sector levels to promote and develop hydrogen technologies. Projects related to the integration of hydrogen with renewable energy sources and the development of hydrogen refueling stations are an undoubted success (Pawłowski, 2022, p. 29). In the context of global efforts to reduce CO2 emissions and local efforts to diversify energy sources, Poland is turning to hydrogen technologies as a key element of its future energy mix (Gawlik, Mokrzycki, 2021, pp. 63-67).

The government plan for hydrogen energy presents ambitious goals aimed at making Poland one of the leaders in this field in Europe.

The development of hydrogen energy in Poland is the result of decades of research, investment and innovation. From early experiments to current applications and initiatives, Poland shows that hydrogen energy is an important and growing element of the national energy strategy. Key projects and technological achievements testify to the country's production capacity and its aspirations to be a leader in the field of hydrogen energy in the region. In the face of challenges related to decarbonisation and the need to diversify energy sources, hydrogen will play a key role in Poland's energy future (Murray, Seymour, Rogut, Zechowska, 2008, pp. 20-27).

The Polish government recognized the potential of hydrogen as a key element of a sustainable energy future and initiated many strategies related to hydrogen energy. This includes the development of a national hydrogen energy strategy that outlines targets for hydrogen production, storage and use by 2030 and beyond (Navaid, Emadi, Watson, 2023).

As a member of the European Union, Poland is obliged to implement EU regulations on hydrogen energy. This includes both commitments to reduce greenhouse gas emissions and the promotion of renewable energy sources, including hydrogen. Poland also participates in international initiatives promoting hydrogen technologies.

The government has introduced various legal acts to support the development of hydrogen energy. These include acts on taxes and reliefs, permits for the construction and operation of hydrogen installations, as well as regulations on research and development. In addition to legislation, there are also various programs and initiatives to support hydrogen energy. These include grants, loans and guarantees for companies and researchers working on hydrogen technologies. These initiatives are aimed at accelerating innovation and commercialization of hydrogen technologies in Poland. Despite positive support from the government, there are some legal barriers that may hinder the development of hydrogen energy. These include complex authorization procedures, lack of harmonized technical standards and possible conflicts with other legislation, such as environmental legislation.

Government policy and regulations in Poland in the field of hydrogen energy are a complex combination of national strategies, EU and international commitments, key legal acts, support initiatives and legal barriers. The government actively supports the development of this technology through a variety of measures, such as tax breaks, subsidies and regulation to promote innovation (Igliński et al., 2022).

However, some legal barriers still exist and require further analysis and intervention to ensure the harmonious development of hydrogen energy. The long-term success of the sector will depend on the skillful balancing of the promotion of hydrogen technologies with compliance with other public policy objectives, such as environmental protection and energy security.

This section shows that hydrogen energy is an important part of Poland's national energy strategy, and the government is taking significant steps to promote and regulate this sector. At the same time, it highlights the challenges and opportunities faced by the sector in terms of regulation and underlines the need for further work to optimize the regulatory environment (Bednarczyk, Brzozowska-Rup, Luściński, 2022).

3. Development of Hydrogen Energy in Germany

The development of hydrogen energy in Germany has a long and rich history. Starting with pioneering research and experimentation in the 1970s (Wali et al., 2023).

Germany has become a world leader in hydrogen technology. For decades, the government has supported research and development, leading to the commercialization of hydrogen technologies in various sectors.

Currently, hydrogen energy is an integral part of the German energy. The country is home to numerous hydrogen projects, including power plants, refueling stations and industrial initiatives. Germany is also a leader in the export of hydrogen technologies.

In Germany, hydrogen energy has found application in various sectors, such as transport, industry and energy. The government also supports initiatives such as public-private partnerships to accelerate technology development.

With strong government support and a dynamic private sector, Germany is well positioned for further development and innovation in the field of hydrogen energy. This is a key element in the country's quest for carbon neutrality and sustainable energy development.

The German government has developed a comprehensive national hydrogen energy strategy that includes goals and guidelines for the development of this sector This strategy is in line with the objectives of the European Union and emphasizes the role of hydrogen in achieving carbon neutrality.

The Poland, Germany is obliged to implement EU regulations on hydrogen energy. Additionally, Germany is an active participant in international hydrogen initiatives and agreements.

In Germany, there are many legal acts and initiatives supporting hydrogen energy, from tax breaks and subsidies to regulations supporting research and innovation (Trencher, Edianto, 2021). These measures aim to create an attractive environment for investment and development.

Despite significant progress, there are some challenges and legal barriers that may affect the further development of hydrogen energy in Germany. These include issues related to safety regulations, technical standards and integration with the existing energy infrastructure.

The development of hydrogen energy in Germany is the result of a long-term commitment to research, innovation and supportive policy. As a result, Germany has created a strong and dynamic hydrogen energy sector, which is a key element of the country's energy strategy. Government policies and regulations create a favorable environment for further development and innovation, but they also require further attention in terms of regulatory challenges and barriers.

4. Analysis of policies and strategies. Comparison of Poland and Germany

Comparing the hydrogen energy policies and strategies of Poland and Germany is a key element in understanding how both countries approach this modern technology. This analysis helps to understand the similarities and differences in the approach, goals, regulations and initiatives of the two countries.

Sustainable development of the energy sector is becoming a key priority for countries around the world, and hydrogen can play a significant role in achieving this goal. Poland and Germany, although at different stages of implementing hydrogen technologies, have taken significant steps towards integrating this energy carrier with their national energy strategies. Comparing government policies, goals, regulations, support initiatives, challenges and implementation strategies in the two countries can provide valuable insights for both practitioners and policy makers.

Table 2. Comparison of Governmental Policies, Goals, Regulations, Support, Challenges and Strategies for the Implementation of Hydrogen Technologies in Poland and Germany presents a detailed analysis broken down by Poland and Germany, taking into account various aspects related to the implementation of hydrogen technologies. This comprehensive table can serve as a reference for further research and analysis in this field. A detailed analysis broken down by Poland and Germany is presented in Table 1 below.

Table 1.
Comparison of Governmental Policies, Goals, Regulations, Support, Challenges and Strategies for the Implementation of Hydrogen Technologies in Poland and Germany

Government Policy and Objectives	
Poland	Poland is actively investing in the development of hydrogen energy, with particular emphasis on research and innovation. National authorities have taken support initiatives within the framework of national plans and strategies, in line with the objectives of the European Union.
Germany	Germany is a leader in hydrogen energy, with a well-defined and comprehensive national strategy. They are also an active participant in international hydrogen initiatives and agreements.
Regulations and Support Initiatives	
Poland	Poland has introduced various regulations and supporting initiatives, such as tax breaks, subsidies and public-private partnerships, to create a favorable environment for investments in hydrogen energy.
Germany	Germany has a more extensive support system, including significant research and development funding, and regulations that promote the commercialization of hydrogen technologies.
Challenges and Barriers	
Poland	Poland faces challenges related to infrastructure, technology availability and integration into the current energy mix.
Germany	Germany, despite its advanced development, also experiences challenges such as safety regulations and technical standards that may affect further development.
Comparison of Strategy and Implementation	
Similarities	Both Poland and Germany consider hydrogen energy to be a key element of their energy strategies. Both countries strive to comply with the objectives of the European Union and actively support the development of hydrogen technologies.
Differences	Germany is much more advanced in the field of hydrogen energy, with a longer history of research and commercialization. Poland, although actively investing in development, is at an earlier stage and focuses more on research and innovation.

Source: Based on (Murray, Seymour, Rogut, Zechowska, 2008, pp. 20-27; Włodarczyk, Kaleja, 2023; Wali et al., 2023; Kochanek, 2022, p. 7235; Lebrouhi et al., 2022; Zhao et al., 2022).

5. Impact of Hydrogen on Sustainable Development

Hydrogen, as a clean and renewable energy source, has the potential to have a major impact on sustainable development. This impact can be understood in the context of various aspects of sustainable development, such as environmental performance, economy and society.

In the era of the global climate crisis, measures to reduce greenhouse gas emissions and promote sustainable development are becoming increasingly important. Hydrogen, as a clean and renewable energy source, has the potential to become a key element in this global transformation.

Table 2. Impact of Hydrogen on Ecology, Economy and Society: Analysis of Emissions, Fossil Fuel Substitution, Cost Efficiency, Economic Impact, Energy Availability, Public Health and Support to Other Renewable Energy Sources and the UN Sustainable Development Goals provides a comprehensive overview of various aspects that can be affected by hydrogen. This includes both environmental benefits such as emission reduction and fossil fuel substitution, as well as economic and social impacts such as cost efficiency, economic stimulus, energy availability and public health.

This table shows the complexity of hydrogen's impact on various areas of sustainability, offering readers an understanding of how hydrogen can be used to achieve wide-ranging environmental, economic and social goals.

Table 2.
Impact of Hydrogen on Ecology, Economy and Society: Analysis of Emissions, Fossil Fuel Substitution, Cost Efficiency, Economic Impact, Energy Availability, Public Health and Support to Other Renewable Energy Sources and the UN Sustainable Development Goals

Ecological Impact	
Reducing Emissions	Hydrogen can be used as a fuel that does not emit carbon dioxide. Therefore, it is of key importance in the pursuit of reducing greenhouse gas emissions and limiting climate change,
Substitution of Fossil Fuels	As an alternative to fossil fuels, hydrogen can play a key role in the decarbonisation of various sectors such as transport, industry and energy.
Economic Impact	
Cost Efficiency	In the long term, hydrogen has the potential to be cost-competitive with traditional fuels. Investments in technology and infrastructure can further reduce,
Stimulating the Economy	The development of hydrogen technologies can lead to the creation of new jobs, increased innovation and economic growth,
Social Influence	
Energy Availability	Hydrogen can help to increase access to energy in remote and deprived regions through local energy production and storage.
Public Health	Reducing fossil fuel-related air pollution through the use of hydrogen can lead to improved public health.

Cont. table 2.

Impact on Other Sustainable Development Goals	
Support for Other Renewable Energy Sources	Hydrogen can be used as a means of storing renewable energy, supporting the integration of other renewable energy sources such as wind and solar power.
Compliance with the UN Sustainable Development Goals (SDGs)	Hydrogen energy is compliant with many of the UN Sustainable Development Goals, such as access to clean energy, climate action and responsible consumption.

Source: Based on (Mneimneh et al., 2023, p. 1368; Kandidayeni, Trovão, Soleymani, Boulon, 2022; Wali et al., 2023; Scheller et al., 2023; Sadik-Zada, 2021; Włodarczyk, Kaleja, 2023; Bridgeland et al., 2022; Spandagos, Reanos, Lynch, 2022; Zhao et al., 2022).

Hydrogen is not only a promising source of energy from a technological and economic point of view, but also plays a key role in the context of sustainable development. Its potential to reduce emissions, support economic growth, improve public health and support other renewable energy technologies has made it a central component of global sustainability strategies. However, the future development of hydrogen energy requires taking into account challenges such as production costs, technology availability, lack of infrastructure and security risks in order to fully realize its potential for sustainable development.

6. Impact of Hydrogen on Sustainable Development in Poland and Germany

Impact of Hydrogen on Sustainable Development in Poland and Germany Hydrogen as an energy source plays a key role in sustainable development, and Poland and Germany are two countries that are actively working to integrate hydrogen into their energy strategies. Table 3 below presents the impact of hydrogen on sustainable development manifested in Poland and Germany.

Hydrogen, being a clean and renewable energy carrier, is becoming a key element of sustainable development strategies around the world. Poland and Germany, two different economies in Europe, are interested in exploring and implementing hydrogen technologies from different perspectives.

Table 3. Impact of Hydrogen on Ecology, Economy and Society in Poland and Germany: Analysis of Emissions, Economic Impact, Social Impact and Support for Other Sustainable Development Goals shows the different approaches of these two countries to hydrogen.

In terms of ecological impact, Poland sees hydrogen as an opportunity to diversify energy sources and reduce CO2 emissions, while Germany is investing in hydrogen technology as a means to further decarbonise the economy. In terms of economic impact, both countries see the opportunity to create new jobs and stimulate innovation, but with varying degrees of commitment and expectations. In terms of social impact, both Poland and Germany see benefits

related to improved air quality and public health, but with different priorities and delivery methods.

This table 3 shows the analysis of differences and similarities between Poland and Germany in the context of hydrogen use, which may provide important lessons for other countries seeking to integrate hydrogen into their sustainable development strategies.

Table 3.
Impact of Hydrogen on Ecology, Economy and Society in Poland and Germany: Analysis of Emissions, Economic Impact, Social Impact and Support for Other Sustainable Development Goals

Ecological Impact	
Poland	Poland, which is largely dependent on coal, sees hydrogen as an opportunity to diversify energy sources and reduce CO2 emissions. The introduction of hydrogen can help meet the country's climate goals.
Germany	Germany, as a leader in the field of renewable energy sources, is investing heavily in hydrogen technology. Hydrogen can help further decarbonise the economy, especially in sectors that are difficult to electrify.
Economic Impact	
Poland	Investments in hydrogen technology can open up new economic opportunities, creating jobs and stimulating innovation.
Germany	Germany is at the forefront of innovation in hydrogen technology and has the potential to be a global leader in this sector, which could contribute to further economic growth.
Social Influence	
Poland	Hydrogen can contribute to improving air quality, especially in urban areas, which can lead to improved public health.
Germany	The integration of hydrogen into the public and private transport system can lead to sustainable mobility and reduction of air pollution.
Impact on Other Sustainable Development Goals	
Poland	The use of hydrogen to store renewable energy can support the development of other renewable technologies, such as wind and solar energy.
Germany	Germany is committed to international hydrogen cooperation, promoting global sustainability and increasing access to clean energy.

Source: Based on (Bałamut, 2022; Kochanek, 2022; Zhao et al., 2022; Stevens, Tang, Hittinger, 2023; Kumar et al., 2022; Stevens, Tang, Hittinger, 2023, pp. 431-441).

In Poland and Germany, hydrogen plays an increasingly important role in the context of sustainable development. Both countries are actively exploring hydrogen opportunities to address the environmental, economic and social challenges they face. Germany, being at the forefront of innovation, is a model for other countries, while Poland is considering the possibilities of hydrogen as part of its energy transition strategy. Cooperation and knowledge exchange between the two countries can contribute to the further development of hydrogen technology internationally, with benefits for both the environment and the economy.

7. Impact of Hydrogen on Sustainable Development in Poland and Germany

The importance of hydrogen as an energy source is attributed to the potential to play a key role in sustainable development, especially in countries such as Poland and Germany, which are actively looking for alternative and green energy sources. The implementation and effective use of hydrogen, while promising, has many potential benefits, but also challenges.

Table 4. Impact of Hydrogen on Sustainable Development in Poland and Germany. Analysis of Potential Benefits and Challenges Related to the Introduction and Efficient Use of Hydrogen as an Energy Source provides a detailed analysis of these aspects.

On the one hand, hydrogen can contribute to the reduction of harmful gas emissions, support renewable energy sources and stimulate economic growth. On the other hand, there are challenges such as the need for significant investments in infrastructure, security standards and technological barriers to entry.

This table 4 shows the complexity of the process of implementing hydrogen as a key element of a sustainable energy strategy, offering a full picture of the opportunities and limitations that Poland and Germany may encounter on this path. This insight can be a valuable tool for policy makers, investors and scientists interested in exploring hydrogen as a key tool in the transition to a cleaner and more sustainable energy future.

Table 4.
Impact of Hydrogen on Sustainable Development in Poland and Germany. Analysis of Potential Benefits and Challenges Related to the Introduction and Efficient Use of Hydrogen as an Energy Source

Potential Benefits	
Reducing Emissions	Hydrogen can make a significant contribution to reducing greenhouse gas emissions, especially in industrial sectors and transport.
Support for Renewable Energy Sources	As an energy store, hydrogen can offset the volatility of some renewable sources such as wind and solar.
New Jobs	Investments in hydrogen technology can create new jobs and stimulate the economy.
Improving Air Quality	Hydrogen in transport and heating can help improve air quality in urban areas.
Increasing Energy Reliability	Hydrogen can increase the reliability of energy supply, especially when combined with renewable sources.
Challenges	
Production costs	Currently, hydrogen production, especially from renewable sources, is relatively expensive, which is a barrier to widespread deployment.
Availability of Technology	Advanced hydrogen technologies are not always available or adapted to local conditions.
Lack of Infrastructure	There is a lack of adequate infrastructure, such as refueling stations, to support a hydrogen-based economy.
Safety Risks	Hydrogen requires special safety precautions during production, transportation and storage, which can be challenging.
Regulations and Policy	Inconsistencies in regulations and government support can inhibit the development of hydrogen energy.

Source: Based on (Kumar et al., 2022; Bridgeland et al., 2022; Evans, Wilson, 2021; Johnston, Mayo, Khare, 2005, pp. 569-585; Kandidayeni, Trovão, Soleymani, Boulon, 2022; Kirchem, Schill, 2023).

Hydrogen has great potential to contribute to sustainable development in Poland and Germany, but its effective implementation requires solving a number of challenges. Both countries need to work to create a favorable environment for investment in hydrogen technology, taking into account both benefits and potential obstacles. Long-term vision, strategic planning, international cooperation and local adaptation will be key to realizing the full potential of hydrogen in the context of sustainable development.

8. Impact of Hydrogen on Sustainable Development in Poland and Germany

Faced with the growing global demand for energy and the need to reduce greenhouse gas emissions, the world is turning to new, sustainable energy sources. Hydrogen, as one of the most promising energy carriers, is gaining importance as part of the green transformation, especially in countries such as Poland and Germany.

In Poland, a country with a rich tradition of coal mining, the hydrogen industry is part of the clean energy transition strategy and can play a key role in minimizing dependence on fossil fuels. Germany, as one of the leading countries in the field of innovation and technology, is also investing in the development of hydrogen technologies, striving to create efficient and sustainable energy systems (Table 5).

Table 5.
Benefits and challenges related to the use of hydrogen technology in Poland

POLAND	
Potential Benefits	
Reducing Emissions	Poland, where coal is the main source of energy, can gain significant benefits from hydrogen in reducing CO2 emissions.
Support for Renewable Energy	Hydrogen can help integrate renewable energy sources such as wind power .
Job creation	The development of hydrogen technology can support the local economy and create new jobs.
Increased Reliability	Improved diversification of energy sources by incorporating hydrogen.
Challenges	
Costs and Availability of Technology	Higher production costs and limited availability of technology in Poland.
Lack of Infrastructure	Need to expand hydrogen infrastructure.
Regulations and Policy	The need for clear and consistent regulations supporting the development of hydrogen energy.
GERMANY	
Potential Benefits	
Green Energy Source	In Germany, with a strong focus on ecology, hydrogen could be a key element of the green transition.
Innovation and Leadership	Germany can leverage its position as a leader in innovation and hydrogen technology.
Support for Renewable Energy	Hydrogen can support Germany's renewable energy targets, especially in the automotive sector.

Cont. table 5.

Challenges	
Integration with Existing Infrastructure	Using hydrogen in existing energy infrastructure can be challenging.
Costs and Competition from Other Sources	Balancing the costs of hydrogen and other competing energy sources.
Security Threats	The need to manage specific security risks associated with hydrogen production and storage.

Source: Based on (Borowski, Karlikowska, 2023; Spandagos, Reanos, Lynch, 2022; Budzianowski, 2012; Kochanek, 2022; Kirchem, Schill, 2023; Egeland-Eriksen, Hajizadeh, Sartori, 2021; Salvi, Subramanian, 2015).

Hydrogen can play different roles in Poland and Germany, with different benefits and challenges. Poland can focus on using hydrogen as a tool to reduce dependence on coal, while Germany can use its position as an innovation leader to promote hydrogen as a green energy source. However, both countries will have to overcome specific challenges to fully realize the potential of hydrogen in the context of sustainable development.

9. Impact of Hydrogen on Sustainable Development in Poland. Case Study: Hydrogen Projects

In Poland, hydrogen energy is gaining in importance as a key element of the sustainable development strategy. In Germany, being one of the leaders of hydrogen technology in Europe, the development of hydrogen energy is a key element of the national energy strategy. Below are some notable hydrogen projects that demonstrate Germany's commitment to this groundbreaking technology. Table 6 below presents some significant hydrogen projects that reflect the diversity and potential of this technology in the Polish and Germany context.

Table 6.
Impact of Hydrogen on Sustainable Development in Poland. Case Study: Hydrogen Projects

Impact of Hydrogen on Sustainable Development in Poland	
"Hydrogen Valley" project in Lower Silesia	It is one of the most ambitious hydrogen projects in Poland, which aims to create an entire ecosystem around hydrogen, combining production, distribution and consumption. This includes the creation of a hydrogen refueling station, a fleet of hydrogen vehicles, and integration with renewable energy sources.
Hydrogen Buses in Warsaw	The capital of Poland has taken the initiative to introduce hydrogen-powered buses to public transport. This project aims to reduce exhaust emissions and show the possibilities of hydrogen transport technology.
Cooperation with Zakłady Chemiczne "Police"	This initiative, carried out in cooperation with a large chemical producer, aims to develop hydrogen production technology from chemical processes. This could lead to more efficient use of hydrogen in various industrial applications.
"Green Hydrogen" project in Pomerania	This project aims to integrate hydrogen production with wind energy in a coastal region. This includes using surplus wind power to electrolyze water and produce green hydrogen.
Education and Research Initiatives	Various universities and research institutes in Poland are conducting projects related to hydrogen, including research into new technologies for the production, storage and use of hydrogen.

Cont. table 6.

Impact of Hydrogen on Sustainable Development in Germany	
H2mobil project	This pioneering project aims to create a national network of hydrogen refueling stations, thus facilitating the transition to hydrogen vehicles. This is part of a wider strategy to promote sustainable transport in Germany.
Hydrogen Lab Bayern (HLB)	This research and development center focuses on developing innovative technologies for the production, distribution and use of hydrogen. It works with industry, government and academia to accelerate the commercialization of hydrogen technology.
Hydrogen Power Plant in Hamburg	This state-of-the-art power plant uses hydrogen to produce electricity, demonstrating hydrogen's potential as a large-scale sustainable energy source. This is part of the city of Hamburg's strategy to become CO2-neutral.
HyFleetCUTE Design	This international project, based in Germany, will investigate the use of hydrogen in commercial vehicle fleets. The knowledge gained will be used to promote hydrogen as an alternative fuel for various types of transport.
Cooperation with Siemens AG in Industrial Projects	Large corporations such as Siemens are investing in hydrogen-related projects, including hydrogen power and manufacturing technologies, demonstrating the growing interest of the private sector in hydrogen technology.
Educational and Academic Initiatives	Various German universities are conducting advanced research on hydrogen technology, creating a platform for innovation and supporting the future development of this field.

Source: Based on (Bałamut, 2022; Bednarczyk, Brzozowska-Rup, Luściński, 2022; Bednarczyk et al., 2022; Reijalt, 2010; Igliński et al., 2022; Panchenko et al., 2023; Kirchem, Schill, 2023; Salvi, Subramanian, 2015; Egeland-Eriksen, Hajizadeh, Sartori, 2021).

Hydrogen projects in Poland are diverse and reflect the wide range of possibilities of this technology. From urban transport to integration with renewable energy sources, hydrogen has the potential to contribute to the sustainable development of Poland on various levels. However, the implementation of these projects requires an integrated strategy, investments and cooperation between various sectors to fully realize the potential of hydrogen in Poland.

Germany plays a key role in the development of hydrogen technology, investing in a wide range of projects from transport to energy. The commitment to innovation, cross-sector collaboration and an integrated approach to the hydrogen strategy makes Germany one of the most advanced countries in this field. These projects not only highlight the potential of hydrogen as a tool for sustainable development, but also point to Germany as a model for other countries seeking to exploit this versatile technology.

10. Impact of Hydrogen on Sustainable Development in Poland and Germany. Future prospects

In Poland, hydrogen energy is a relatively new area, but the potential and interest in the technology is growing. Below we present the prospects for the future of hydrogen energy in Poland, both in terms of sustainable development and in the economic, social and environmental context. In Germany, as one of the leaders in renewable energy and sustainability, hydrogen has great potential to play a key role in the country's future energy mix. Here are the prospects for the future of hydrogen energy in Germany (Table 7).

Table 7.
Impact of Hydrogen on Sustainable Development in Poland and Germany. Future prospects

POLAND	
Integration with Renewable Energy Sources	In Poland, there is a noticeable trend towards increased production of energy from renewable energy sources (RES). Hydrogen can become a key element in RES integration, enabling the storage of excess energy and stabilization of the power grid.
Development of Transport Infrastructure	Planning and implementing infrastructure for hydrogen transport, such as refueling stations, can drive the development of the hydrogen vehicle sector, in line with the global trend to decarbonize transport.
Investments in Research and Development	Increasing investment in hydrogen research and development, both at the government and private level, can accelerate innovation and reduce the cost of hydrogen technology.
Regulatory and Policy Support	Active government support, including incentives and regulation, can drive the growth and commercialization of hydrogen technology in Poland, supporting both the country's environmental and economic objectives.
International cooperation	Participation in international initiatives and cooperation with neighboring countries can enable the exchange of knowledge and technology, as well as increase the scale and efficiency of hydrogen implementations.
Education and Social Awareness	Raising social awareness and education about hydrogen as a sustainable energy source can contribute to social acceptance and further development of the market.
GERMANY	
Leader in Hydrogen Technology	Germany is already considered a leader in hydrogen technology in Europe. Further investment and support for research and development can strengthen this position in the international arena, creating opportunities to export technology and knowledge.
Integration with the Energy Grid	Hydrogen can play a key role in storing renewable energy and ensuring grid flexibility, supporting Germany's transformation towards a low-carbon economy.
Sustainable Transport and Industry	The use of hydrogen in the transport sector and industry can contribute to a significant reduction in greenhouse gas emissions. The development of hydrogen infrastructure in these sectors is key to meeting Germany's climate goals.
International Cooperation	Germany can increase its partnerships and cooperation with other European and global countries in the field of hydrogen technology by promoting standards and best practices around the world.
Hydrogen Policy and Regulations	The adoption of an integrated hydrogen policy and regulation, in line with the EU's sustainable development goals, can provide long-term certainty and stability for investors and businesses.
Society and Education	Building public awareness and understanding about the benefits and applications of hydrogen as a sustainable energy source can contribute to social acceptance and promote hydrogen technologies in everyday life.

Source: Based on (Bhandari et al., 2021; Hassan et al., 2023; Panchenko et al., 2023; Salvi, Subramanian, 2015; Kirchem, Schill, 2023; Egeland-Eriksen, Hajizadeh, Sartori, 2021).

Poland faces an exciting opportunity to become a key player in the field of hydrogen energy in Europe. Long-term success will require an integrated approach combining policy, investment, innovation and education. Using its rich energy resources and innovative spirit, Poland can play an important role in the global energy transformation, using hydrogen as a sustainable development tool for the future.

In Germany, the prospects for hydrogen energy are promising and in line with the country's long-term vision for a sustainable economy. With the right political support, investment, innovation and education, hydrogen can play a key role in Germany's energy transition. Given the growing global focus on decarbonisation and sustainable development, Germany has the potential to become a global leader in hydrogen energy, setting the stage for other countries and contributing to the global Sustainable Development Goals.

11.Analysis of the survey on Hydrogen Energy in Poland and Germany

The survey was designed to explore the understanding of the public and various stakeholders in the field of hydrogen energy. This is often a new and unfamiliar field for many people, so understanding how people view hydrogen as an energy source, what benefits and challenges they see can provide important clues for policy makers, scientists and entrepreneurs.

Hydrogen energy is becoming an increasingly important area in the global energy transformation. However, public opinion and attitudes towards hydrogen may vary depending on national context, education, experiences and values. Poland and Germany, although they are neighbors and part of the same European Union, have different energy traditions, strategies and goals. These differences may affect how hydrogen energy is perceived in both countries. In the survey on hydrogen energy in Poland and Germany, proper sample selection and representativeness are key to obtaining reliable and generally applicable results. Here is how these aspects were applied and why they are relevant in the context of this study: Poland (898 respondents): The sample was selected in such a way as to reflect the demographic diversity of Poland, taking into account factors such as age, gender, education, place of residence and interest and experience in the field of energy.

Germany (924 respondents): As in Poland, the German sample was structured to reflect the diversity of the country. It covered various social groups, regions and levels of understanding and involvement in hydrogen energy.

Representativeness in a survey study refers to the extent to which the research sample reflects the general population from which it was drawn. This is a key aspect that determines whether survey results can be generalized to the entire population. In the context of the hydrogen energy study in Poland (898 respondents) and Germany (924 respondents), representativeness can be understood by applying the following formulas and concepts.

Sample size (n): This is the number of units in the sample, i.e. 898 for Poland and 924 for Germany.

Population Size (N): This is the total number of units in the population from which the sample was drawn. It could be the total number of adult citizens in both countries, for example.

- Margin of Error (e): The margin of error expresses how far the results of a sample may differ from the actual results of the population as a whole. The standard margin of error is often 5% or 3%.
- Confidence Level (Z): This is the Z-score corresponding to the desired confidence level, often 95% or 99%.
- Standard Deviation (σ): This is a measure of the dispersion of results in the sample.
- Sample Size Calculation Formula:

sample size - Z-score value - standard deviation - population size - margin of error

$$n = \frac{Z^2 \cdot \sigma^2 \cdot (N - n)}{e^2 \cdot (N - 1) + Z^2 \cdot \sigma^2}$$

where:

n - sample size,

Z - Z-score value,

σ - standard deviation,

N - population size,

e - margin of error.

For this particular study, the appropriate values for: N, e, Z and σ should be selected based on the purpose of the study and the characteristics of the population to achieve adequate representativeness. The selection of 898 and 924 respondents for Poland and Germany must comply with these parameters to ensure that the results are reliable and can be generalized to the wider population in both countries. In both countries, the sample was structured to include a variety of social groups, including industry experts, policy makers, academia, entrepreneurs, and the general public. Efforts were made to make the sample demographically balanced, in line with national statistics, so that the results could be generalized to a wider population.

Although the number of respondents in Poland and Germany was slightly different, this difference is not significant and does not affect the ability to compare results between the two countries. The diversity of perspectives across different age groups is essential for a comprehensive understanding of attitudes towards hydrogen energy in Poland and Germany. The distribution of respondents across various age brackets is illustrated in Figure 1. This age analysis ensures a wide-ranging insight into the opinions and perceptions across generations, enriching the study's conclusions about hydrogen's role in sustainable development.

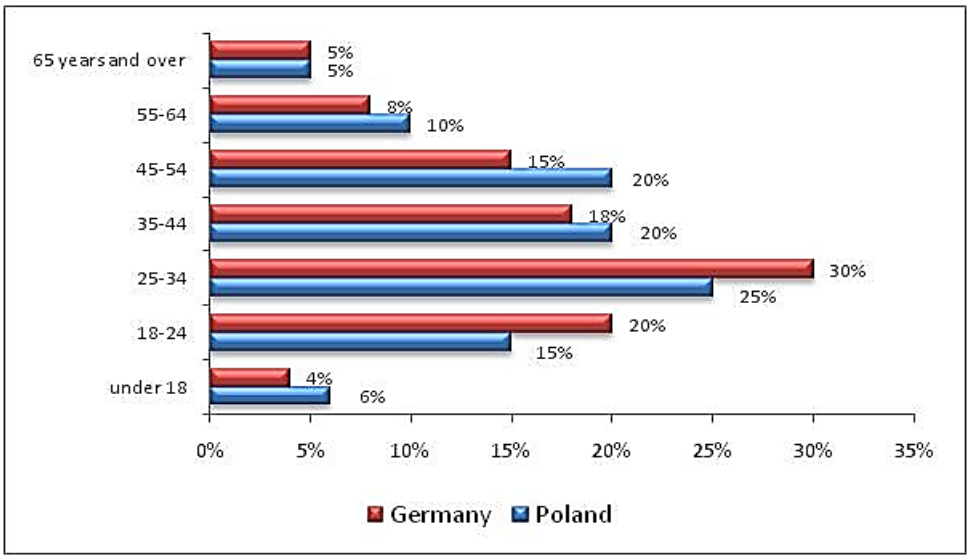

Figure 1. Analysis of respondents in Poland and Germany in terms of age.

Source: Research led by the Author.

Interpreting the age results in Poland and Germany, it can be seen that both countries have similar proportions in age groups, but there are some differences. In the 18-24 age group, Germans have a higher percentage (20%) compared to Poland (15%), which may indicate a larger young adult population. This difference also persists in the 25-34 age group, where Germany has 30% and Poland 25%. In the 35-44 and 45-54 age groups, Poland has slightly higher percentages than Germany, which may suggest that Poland has more middle-aged people. In terms of people aged 55 and over, both countries have relatively similar percentages, with a slight advantage for Poland in the 55-64 age group.

These results may reflect differences in the demographic structure between Poland and Germany, with a higher percentage of younger people in Germany and a slightly higher percentage of middle-aged people in Poland. These differences can have implications for various aspects of society, such as the labor market, education or social policy.

The variation in opinions on hydrogen energy can often be influenced by educational background. Figure 2 illustrates the level of education of respondents in Poland and Germany, providing insights into how educational attainment might shape perspectives and understanding of hydrogen technologies in both countries.

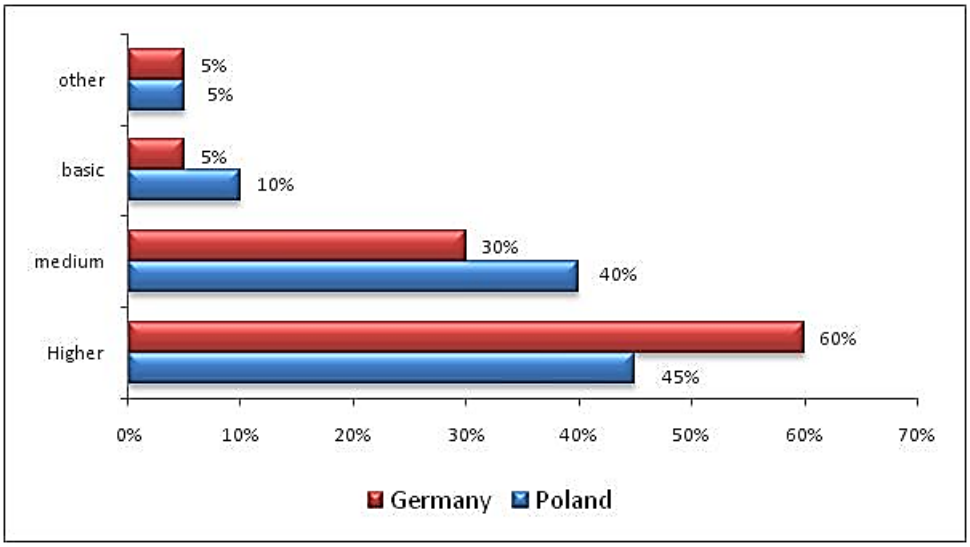

Figure 2. Level of education of respondents in Poland and Germany.

Source: Research led by the Author.

When interpreting the results concerning education in Poland and Germany, significant differences can be noticed in the structure of education of citizens of both countries. In Poland, a higher percentage of respondents report secondary education (40%) compared to Germany (30%). Meanwhile, Germany has a significantly higher percentage of people with higher education (60%) compared to Poland (45%). In the category of primary education, Poland has a double percentage (10%) compared to Germany (5%), which may indicate differences in education systems and access to further education. Also, the percentages in the category "Other" are identical for both countries at 5%, which may reflect non-standard educational paths or specific qualifications.

These results may suggest that in Germany there is a greater tendency to obtain higher education, while in Poland secondary education may be more common. These differences can affect various socio-economic aspects, such as job mobility, earnings and investment in education.

Understanding the public's knowledge of hydrogen as a source of energy is essential in assessing its potential adoption and support. Figure 3 provides an analysis of the knowledge on hydrogen energy in Poland and Germany, shedding light on the current awareness and comprehension of this emerging technology in both nations.

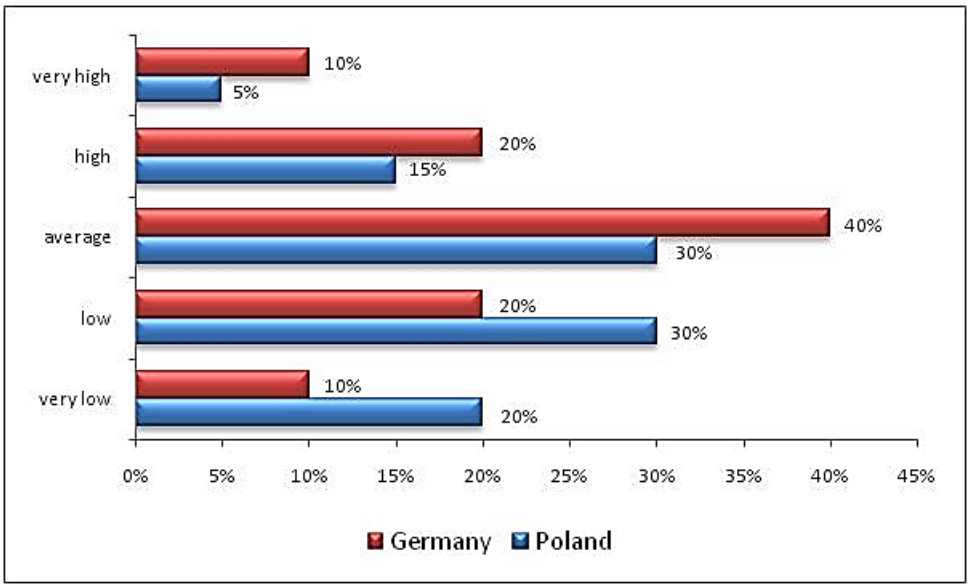

Figure 3. Analysis of knowledge on Hydrogen as a Source of Energy in Poland and Germany.
Source: Research led by the Author.

Analyzing the results regarding the assessment of knowledge about hydrogen as an energy source in Poland and Germany, some differences between the citizens of both countries can be observed. In Poland, the percentage of people who consider their knowledge to be "very low" or "low" is much higher (50% in total) compared to Germany (30% in total). This may indicate less exposure to topics related to hydrogen energy in Poland or differences in education and promotion of this topic. In Germany, a greater proportion of respondents (70% in total) rate their knowledge of hydrogen as an energy source as "medium", "high" or "very high", compared to Poland (50% in total). This may indicate greater awareness and education on hydrogen energy in Germany.

Overall, these results may suggest that there is a better understanding and perhaps a greater commitment to hydrogen energy topics in Germany. These differences may be the result of differences in education policy, investment in research and development, as well as in the methods of communication and promotion of hydrogen technologies in both countries. Identifying where people obtain information about hydrogen energy is critical in understanding public perception and beliefs about this technology.

Figure 4 illustrates the sources of information on hydrogen energy in Poland and Germany, offering insights into the channels that influence opinions and knowledge in these countries.

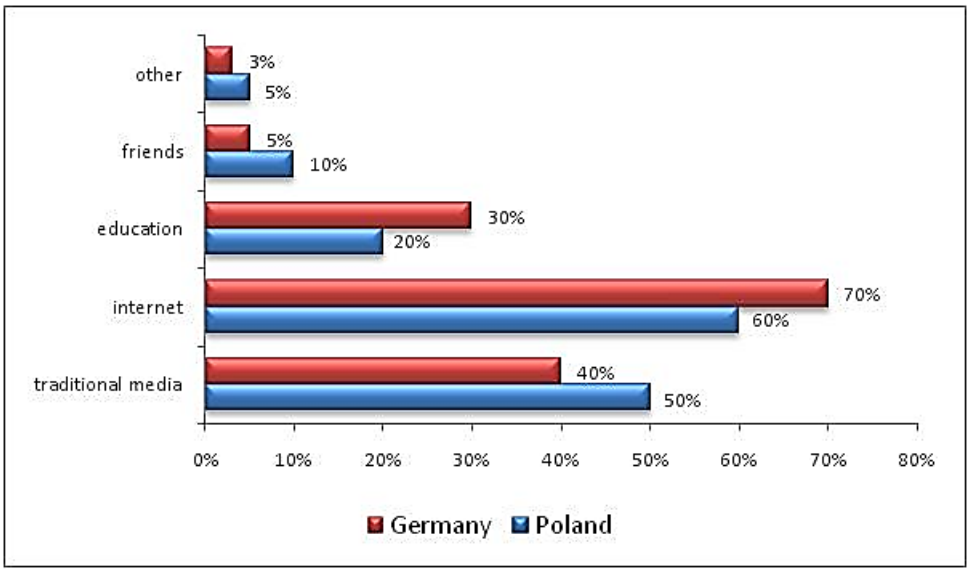

Figure 4. Sources of information on hydrogen energy in Poland and Germany.
Source: Research led by the Author.

Upon analyzing the sources of information on hydrogen energy in Poland and Germany, one can observe notable differences and similarities. In Poland, a higher proportion of individuals (50%) rely on traditional media for information compared to Germany (40%). This suggests that traditional media exert a more significant influence on shaping public opinion about hydrogen energy in Poland. In both nations, the internet and social media serve as the predominant sources of information on hydrogen energy. However, the percentage is marginally higher in Germany (70%) than in Poland (60%), potentially indicating a more engaged and integrated online community in Germany.

Germany also has a higher proportion of individuals (30%) who acquire information from the educational system compared to Poland (20%). This discrepancy may reflect divergent educational priorities and emphasis on renewable energy topics, including hydrogen, in the educational systems of the two countries.

Poland exhibits greater reliance on information obtained from friends and family (10%) compared to Germany (5%), possibly highlighting cultural variances in communication styles and trust in different information sources. In both countries, "Other" sources of information are relatively insignificant, although Poland has a slight edge (5%) over Germany (3%).

Collectively, these disparities may be indicative of cultural, educational, and media differences between Poland and Germany. Germany appears to be more integrated with the internet and educational systems as primary sources of knowledge about hydrogen energy, whereas in Poland, traditional media and social relationships play a more significant role.

Understanding public sentiment toward the utilization of hydrogen as an energy source is crucial for shaping policy and outreach strategies. Figure 5 offers an overview of the general stance on hydrogen use in Poland and Germany, reflecting public attitudes and acceptance of this emerging energy solution.

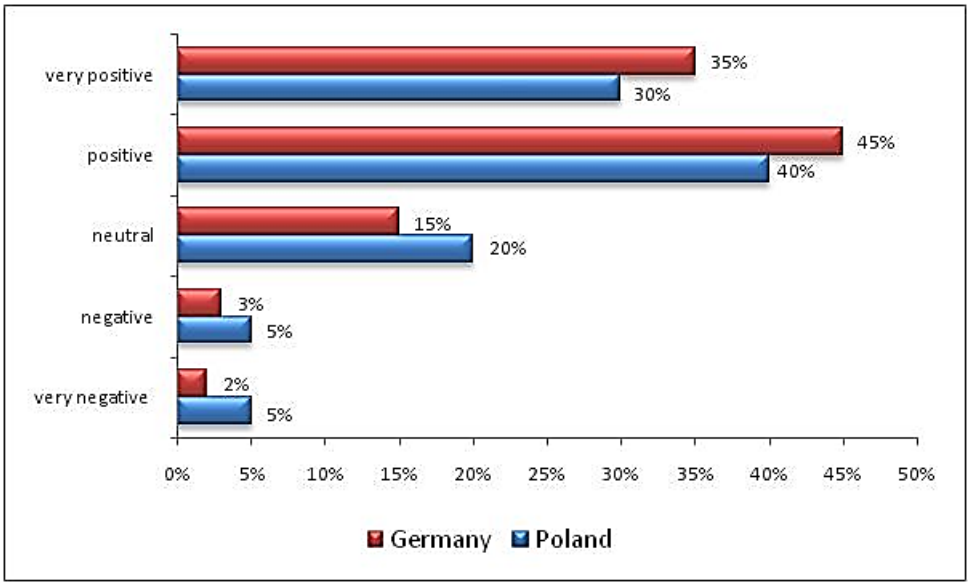

Figure 5. General position on the use of hydrogen as an energy source in Poland and Germany.
Source: Research led by the Author.

The answers to the question about the general position on the use of hydrogen as an energy source in Poland and Germany show a generally positive attitude in both countries. In Germany, the overall position is slightly more positive compared to Poland, with a higher proportion of respondents expressing positive and very positive views.

Positive feelings also dominate in Poland, but there is also a larger percentage of people expressing a neutral position. Negative and very negative opinions are relatively rare in both countries, suggesting a generally positive perception of hydrogen as an energy source in both Poland and Germany.

Government investment plays a critical role in advancing hydrogen technology and facilitating its integration into the energy system. Figure 6 offers a comparison of opinions on government investments in hydrogen technology in Poland and Germany, shedding light on public support or criticism of these strategic initiatives.

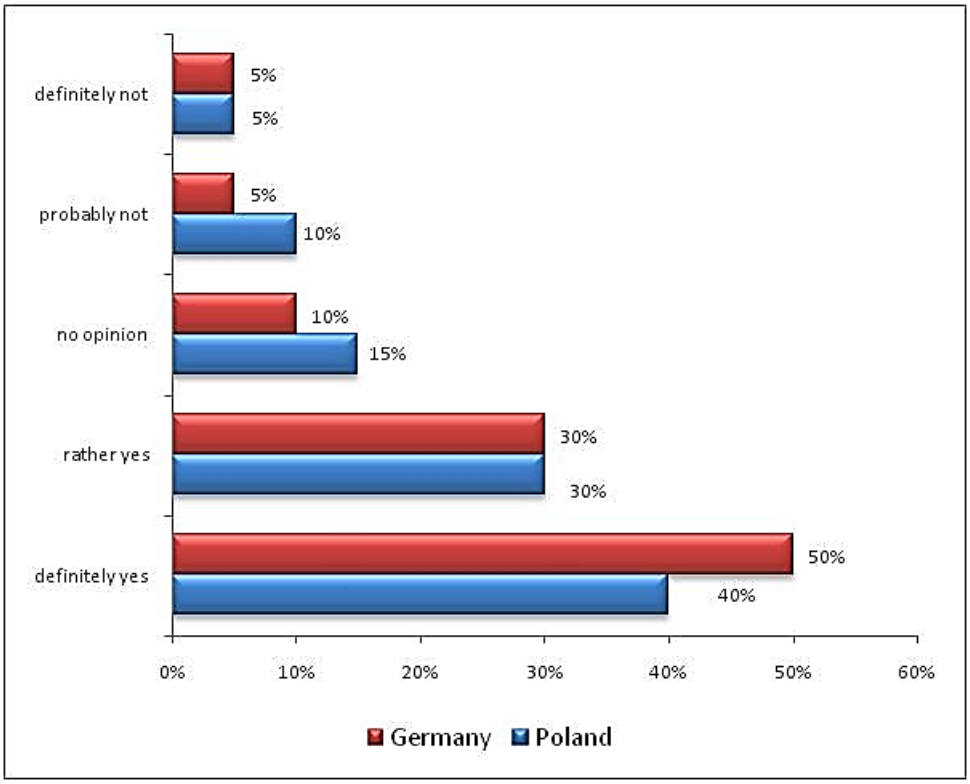

Figure 6. Comparison of Opinions on Government Investments in Hydrogen Technology in Poland and Germany.

Source: Research led by the Author.

The answer to the question about readiness to personally support the development of hydrogen energy in Poland and Germany shows the diversity of opinions. 30% of respondents in Poland and 40% in Germany strongly support the development of hydrogen energy. This indicates the existence of a strong supporter base in both countries, particularly in Germany, who may be interested in actively participating in this field. An additional 30% in both Poland and Germany express moderate support, increasing the total number of supporters in both countries. 20% of Poles and 15% of Germans have no opinion on this issue, which may reflect a lack of information, understanding or commitment to the issue. 15% of respondents in Poland and 10% in Germany are unlikely to support this idea, and 5% in both countries are strongly against it. These figures indicate that there is some opposition, but it is not dominant.

The higher level of strong support in Germany may reflect more advanced hydrogen technology development and better education on hydrogen as an energy source in the country. There is also significant support in Poland, suggesting that there may be potential to increase support through education and public involvement. The neutrality of a significant proportion of respondents may indicate the need for further education and awareness in this area to enable more informed decisions.

Overall, many more people seem to support hydrogen energy than oppose it, suggesting an overall positive trend towards the technology in both countries.

These results indicate that there is an understanding and interest in hydrogen energy in both countries, but also underline the importance of education, communication and social involvement in the further development and adoption of this technology.

Understanding the perceived advantages of hydrogen as an energy source is vital for shaping policies and public engagement strategies. Figure 7 illustrates the advantages of hydrogen as an energy source according to respondents from Poland and Germany, providing insights into what features are considered most valuable in these two countries.

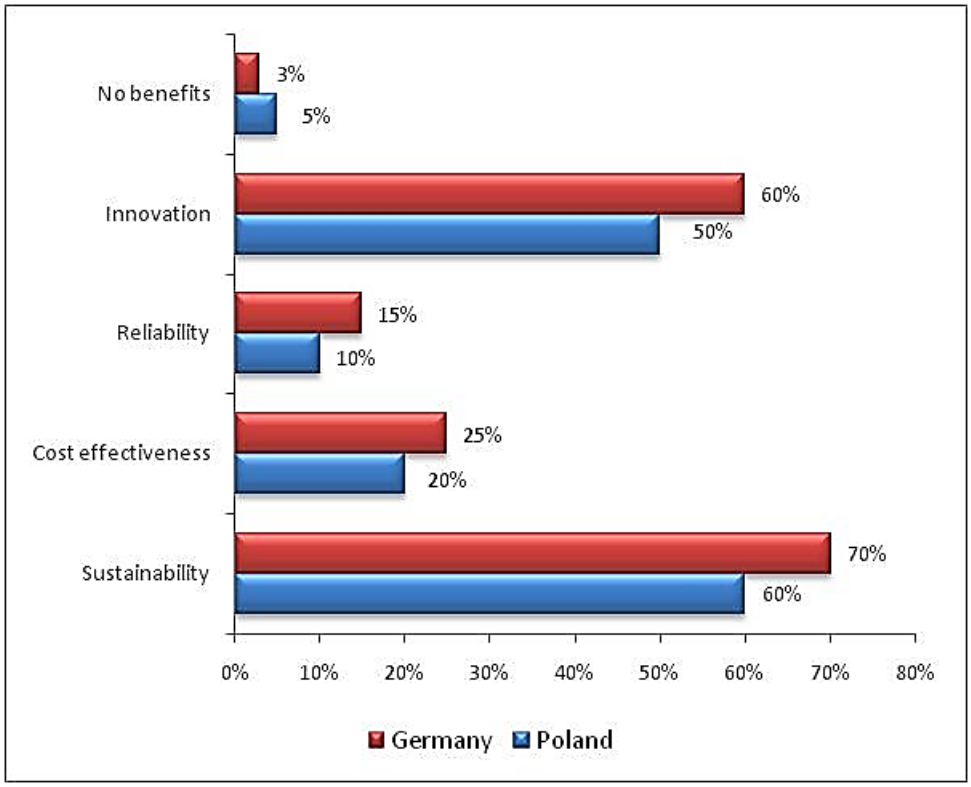

Figure 7. Advantages of hydrogen as an energy source in the opinion of respondents from Poland and Germany.

Source: Research led by the Author.

In analyzing the main benefits of hydrogen as an energy source, both Polish and German respondents point to several key aspects: Most Poles (60%) and Germans (70%) consider environmental friendliness to be the main benefit of hydrogen. This reflects the global trend and emphasis on sustainable and clean energy sources. For 50% of Poles and 60% of Germans, innovation is an important asset of hydrogen energy. This may indicate the perception of hydrogen as a technology of the future, related to scientific and technological progress. Fewer respondents, but still a significant proportion, see cost-efficiency as a benefit, respectively 20% in Poland and 25% in Germany. This may indicate the growing recognition of hydrogen as a potentially competitive energy source.

Germans (15%) are slightly more likely than Poles (10%) to point to reliability as their main benefit, which may reflect different experiences and expectations in these countries.

A small percentage in both countries (5% in Poland and 3% in Germany) do not see any benefits from hydrogen as an energy source, which may suggest some communication challenges or a lack of understanding of the technology. Sustainability and innovation are clearly common values in both countries, highlighting the importance of sustainable development and innovation in public perception. Differences in perceptions of reliability and cost-effectiveness may reflect the unique economic and energy contexts of the two countries.

The small percentage of people who do not see the benefits may indicate the need for better communication and education regarding hydrogen, its possibilities and role in the future energy mix.

Overall, these results seem to emphasize that the societies of both Poland and Germany see significant potential in hydrogen energy, especially in the context of ecology and innovation, but also in other aspects that may differ between these countries. Assessing the challenges related to hydrogen as an energy source is essential for overcoming barriers and facilitating its adoption. Figure 8 presents an analysis of the main challenges associated with hydrogen energy in Poland and Germany, based on our own research, shedding light on the obstacles perceived in both nations.

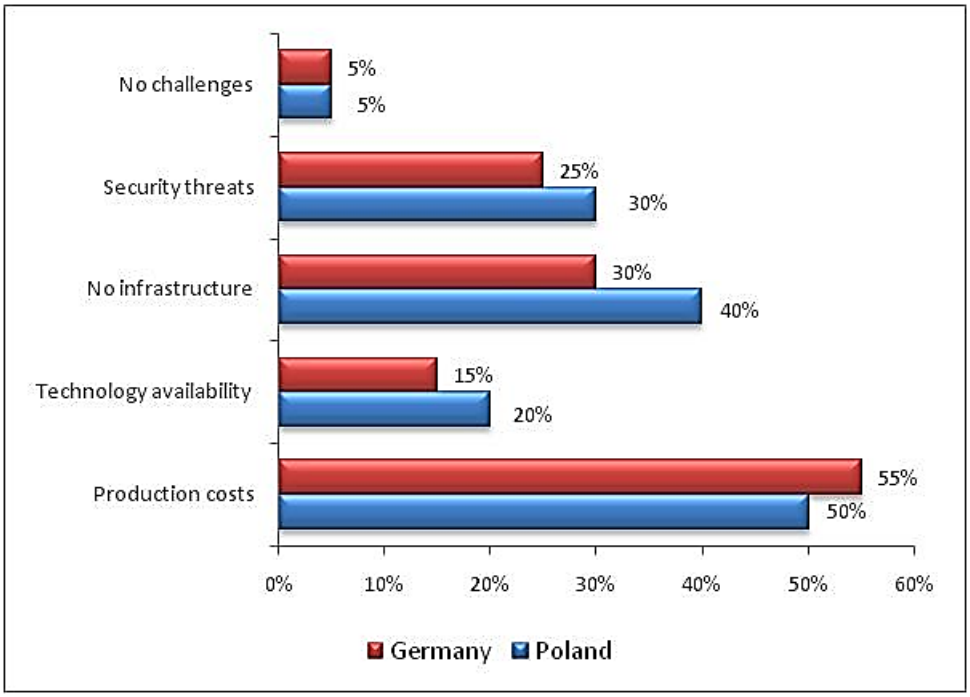

Figure 8. Analysis of the main challenges related to hydrogen as an energy source in Poland and Germany.

Source: Research led by the Author.

In an analysis concerning the primary challenges associated with hydrogen as an energy source, respondents from Poland and Germany identified several key areas. Production costs were highlighted by 50% of the Polish respondents and 55% of the German respondents, indicating a pervasive perception that costs could be a barrier to the social acceptance of hydrogen technologies. A lack of infrastructure was cited by 40% of respondents in Poland and

30% in Germany, suggesting an awareness of the substantial infrastructure investments required for hydrogen energy technologies. Security concerns were noted by 30% of Polish respondents and 25% of German respondents, potentially reflecting apprehensions about the introduction of new technologies and the necessity for adequate risk management. Additionally, 20% of respondents in Poland and 15% in Germany identified the availability of technology as a challenge, possibly indicating perceived technological barriers in the development of hydrogen energy.

Interestingly, a minor percentage of respondents in both countries (5%) did not identify any challenges, which could signify variations in perception and awareness. Production costs were commonly cited in both nations, potentially reflecting broader concerns about the economic viability of hydrogen as an emerging energy source.

Divergences in the perception of other challenges, such as infrastructure and security, could be attributed to cultural differences, energy policies, and market experiences in these countries. These findings may also underscore the necessity for enhanced education and communication regarding hydrogen technologies to manage perceptions of risks and challenges appropriately.

In summary, the data reveal that both Polish and German populations are cognizant of the challenges associated with hydrogen as an energy source. However, the weighting and perception of these challenges may vary depending on the national context. The role of government investments in shaping the future of hydrogen energy is also significant. An analysis of opinions on governmental investments in hydrogen technology, based on the research conducted, highlights the perspectives and expectations of respondents in these two countries.

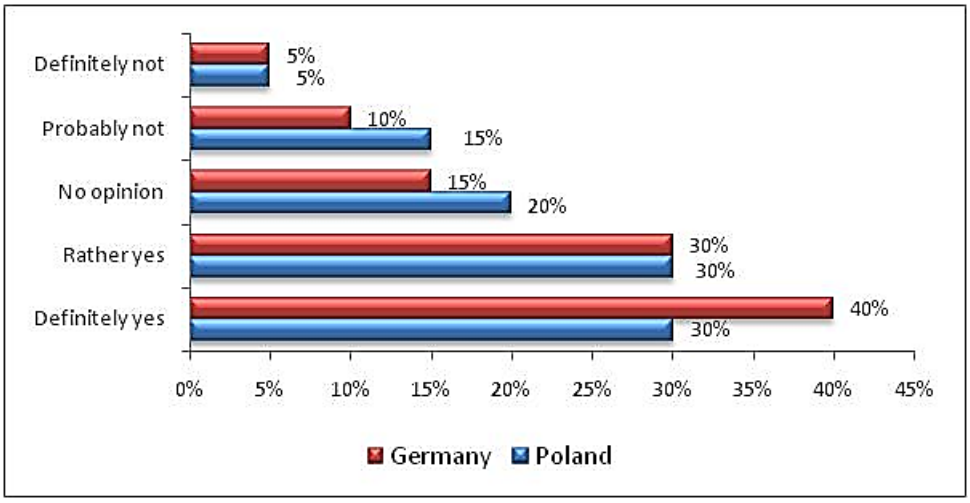

Figure 9. Analysis of opinions on government investments in Poland and Germany.
Source: Research led by the Author.

In Poland, the vast majority of respondents express support for increasing government investment in the development of hydrogen technologies, with 40% definitely yes and 30% rather yes. Germany shows even more support, with 50% definitely yes and 30% rather yes. A neutral position is expressed by 15% of Poles and 10% of Germans. Opinion against

increasing investment is relatively low in both countries, with 10% rather not and 5% definitely not in Poland, and 5% rather not and 5% definitely not in Germany.

These data indicate that there is strong public support for increased government investment in hydrogen technologies in both countries, which may reflect the growing understanding and acceptance of hydrogen as a key energy source in the future. The higher level of strong support in Germany may indicate a greater willingness of the public to introduce more ambitious measures in the area of hydrogen energy. A small number of respondents in both countries express opposition to increased investment, which may suggest that there are no significant social or political barriers against this direction. These data can provide important clues to policy makers in both countries as to the potential direction and intensity of hydrogen policies.

Overall, these results seem to suggest that both Poland and Germany are on track to increase investment in hydrogen technologies, with strong public support for such an initiative. In Germany, this support is slightly stronger, which may reflect differences in perceptions and experiences with hydrogen technology.

12.Discussion

Hydrogen Technology Trend: There has been a significant global trend in recent years towards the development and adoption of hydrogen technologies as a new and sustainable energy source.

Part of Global Sustainability Movement: This boom in hydrogen technology is not an isolated phenomenon but is linked to a broader global movement towards sustainability. This recognizes the decreasing sustainability of traditional energy sources like oil and coal. Complex Analysis Required: The role of hydrogen in sustainable development cannot be understood solely through a technological lens. It must be analyzed from political, economic, social, and environmental contexts as these are interrelated and influence how hydrogen is utilized. Two Case Studies - Poland and Germany: The text emphasizes the importance of comparing and contrasting the role of hydrogen energy within two specific national contexts: Poland and Germany. These countries, although different in many respects, present an interesting study due to their active pursuit of hydrogen technology within the shared framework of the European Union's CO2 reduction goals.

Broader Context Understanding: It emphasizes the importance of understanding hydrogen beyond just an energy source, exploring the theoretical frameworks that explain its importance in the modern energy landscape, potentially redefining our approach to energy and sustainability.

Not Just Technical: The study of hydrogen technology should not be limited to its technical and engineering aspects. It should delve deeper into understanding how hydrogen fits into the larger sustainability narrative, exploring potential benefits and challenges, and how it can be applied in different national and international contexts.

Unified Interest but Diverse Approaches: Despite a unified interest across different regions, including European countries like Poland and Germany, there are varying approaches to achieving sustainability goals through hydrogen, reflecting the unique economic, political, and cultural conditions of individual nations and regions.

In summary, the text portrays hydrogen technology as a multifaceted and critical element in the global shift towards sustainable energy. It emphasizes the importance of a comprehensive and contextual analysis to understand its role, potential, and challenges in different national scenarios.

Hydrogen energy research and development in Poland began in the 1970s, focusing on storage, transport, and usage. Investments and key projects in the 1990s have contributed to the country's expertise in this field (Kowalski, 2002; Szczepanski, 1995; Lewandowski, 2000). In the past two decades, hydrogen has gained prominence in Poland's energy landscape, being seen as vital for decarbonization and playing roles in industry and transport.

Poland is experiencing rapid growth in hydrogen energy, with successful initiatives at both governmental and private levels, such as integration with renewable sources and the establishment of refueling stations. The Polish government has recognized hydrogen's potential, setting ambitious goals to become a leader in Europe and outlining targets for hydrogen usage up until 2030 and beyond. The government has implemented various legal acts to support the development of hydrogen energy, including tax breaks, permits, and research regulations. Alongside this, there are support initiatives such as grants and loans to accelerate innovation. Despite the positive support, legal barriers exist that may hinder development, including complex authorization procedures and potential conflicts with environmental legislation. As an EU member, Poland must comply with EU regulations regarding hydrogen energy, including commitments to reduce emissions and promote renewables, and it actively participates in international initiatives.

The success of hydrogen energy in Poland will require a delicate balance between promotion and compliance with other public policy objectives, recognizing that some legal barriers still need to be addressed.

The text illustrates how hydrogen is a significant part of Poland's national energy strategy, reflecting decades of research, investment, policy support, and innovation. The country's ambition to be a regional leader in hydrogen energy is clear, backed by governmental plans and support mechanisms, though challenges remain that require further analysis and strategic planning. In essence, Poland's journey with hydrogen energy is marked by progressive growth, robust governmental support, alignment with international commitments, and the recognition of both the opportunities and challenges that lie ahead in shaping a sustainable energy future.

Germany has been at the forefront of hydrogen technology since the 1970s, demonstrating a long-standing commitment to pioneering research, experimentation, and commercialization. Hydrogen energy is an essential part of the German energy strategy. The country's focus on hydrogen reflects its position as both a domestic priority and an export opportunity. Germany's hydrogen technologies have found applications in various sectors, including transport, industry, and energy. This reflects a multifaceted approach to integrating hydrogen into the national energy framework. Germany's government has been actively supporting hydrogen energy through research, development, public-private partnerships, and a comprehensive national hydrogen strategy aligned with the EU's objectives.

Numerous legal acts and initiatives, such as tax breaks and subsidies, have been introduced to support hydrogen energy. However, challenges related to safety regulations, technical standards, and energy infrastructure integration must be addressed. Germany aligns with and actively contributes to EU regulations on hydrogen energy. Its participation in international agreements emphasizes its leadership role in the global hydrogen energy landscape.

Hydrogen energy is considered a vital element in Germany's pursuit of carbon neutrality and sustainable development. This aligns hydrogen technology with broader environmental and societal goals. Germany's hydrogen energy development showcases a dynamic balance between innovation and supportive policy. While the sector's success is evident, there is recognition that regulatory challenges and barriers must be addressed to maintain growth and leadership in the field.

With both government and private sector engagement, Germany is well-positioned for further innovation in hydrogen energy. The collaborative approach indicates a holistic understanding of the role of hydrogen in the country's future energy needs. In summary, Germany's development of hydrogen energy is marked by historical leadership, strategic integration into national energy goals, multifaceted applications, strong government support, alignment with international objectives, and a clear path towards future sustainability and innovation. Despite existing challenges and legal barriers, the commitment to research, investment, and policy support signifies Germany's role as a global leader in hydrogen energy and its importance in the nation's pursuit of sustainable energy development.

Poland is focusing on the development of hydrogen energy through research and innovation, aligning with EU objectives. Germany is leading in this field with a comprehensive national strategy and active international participation. Poland has introduced various regulations and initiatives to promote hydrogen investment, while Germany offers more extensive support, including significant research funding. Both Poland and Germany face challenges in developing hydrogen energy, with Poland struggling with infrastructure and technology, and Germany with safety regulations and standards. Both countries consider hydrogen energy crucial to their energy strategies and comply with EU objectives, but Germany is more advanced with a history of research and commercialization, while Poland is in earlier stages. Hydrogen energy has the potential for significant impact on sustainable development, including reducing emissions,

economic stimulation, enhancing public health, and alignment with UN Sustainable Development Goals. However, realizing its full potential requires overcoming challenges such as production costs, technology availability, and security risks.

In Poland and Germany, hydrogen is emerging as a vital component in achieving sustainable development goals. Poland views hydrogen as a means to diversify energy sources, reduce emissions, and stimulate economic opportunities. Germany, a leader in renewable energy, sees hydrogen as a tool for further decarbonization and global leadership in economic growth. Both countries also acknowledge the potential social benefits of hydrogen, such as improved air quality and sustainable mobility. The commitment to international cooperation and the development of renewable technologies demonstrates a shared vision for a sustainable future.

Hydrogen energy presents a promising opportunity for sustainable development in both Poland and Germany, with the potential for reducing emissions, supporting renewable energy, creating jobs, improving air quality, and increasing energy reliability. However, the realization of these benefits is contingent on overcoming several challenges, including high production costs, limited technology availability, lack of infrastructure, safety risks, and regulatory inconsistencies. Strategic planning, investment, cooperation, and careful consideration of local conditions will be vital in harnessing hydrogen's full potential for sustainable development in these countries.

In Poland, hydrogen offers promising benefits, such as reducing emissions in a coal-dependent country, supporting renewable energy integration, creating jobs, and increasing energy reliability. However, realizing these benefits requires overcoming challenges such as high production costs, limited technology availability, a lack of infrastructure, and the need for clear regulations to support hydrogen energy development.

For Germany, hydrogen could be a key element in its green transition, offering a green energy source, reinforcing its leadership in innovation, and supporting renewable energy targets, especially in the automotive sector. Challenges include the integration of hydrogen with existing infrastructure, cost balancing with other energy sources, and managing specific security risks associated with hydrogen production and storage. Both countries will need targeted strategies and collaboration to overcome these obstacles and harness the full potential of hydrogen energy.

Poland is showing growing interest in hydrogen energy, with opportunities in integrating renewable energy sources, developing transport infrastructure, and investing in research and development. Government support, international cooperation, and public education will be key to driving the growth and commercialization of hydrogen technology. With the right strategy, Poland could become a significant player in the European hydrogen landscape.

Germany, already a leader in hydrogen technology, has great potential to further integrate hydrogen into its energy grid, transport sector, and industry. Continued investment, international cooperation, clear policies, and public awareness will strengthen its leading position. Hydrogen can play a vital role in Germany's transition towards a sustainable economy

and enhance its global leadership in the field. Both countries, though at different stages of development, have the potential to reap significant benefits from hydrogen energy. Collaborative efforts and strategic planning will be essential in realizing this potential in alignment with sustainability goals. There's an overall positive perception of hydrogen energy in both Poland and Germany. However, awareness and understanding are higher in Germany, reflecting possible differences in education and promotion. Similar age demographics exist in both countries, with a younger population in Germany and a more middle-aged population in Poland. Education structures differ significantly, with Germany having more people with higher education.

Traditional media has greater influence in Poland, while Germany leans more towards the internet and educational systems for information on hydrogen energy. This suggests cultural and educational differences between the two countries. Both countries show a strong support base for hydrogen energy development, particularly in Germany. A significant proportion of neutrality indicates the need for further education and awareness.

Respondents in both nations consider environmental friendliness and innovation as primary benefits of hydrogen energy. There's recognition of hydrogen as a potential competitive energy source, although perceptions of reliability and cost-effectiveness vary between the two nations. Both societies are aware of challenges related to hydrogen, including production costs and lack of infrastructure. Perceptions of these challenges may differ based on culture, energy policy, and market experience. There's strong public support for increased government investment in hydrogen technologies in both Poland and Germany. The higher level of support in Germany may indicate a greater willingness to introduce ambitious measures in hydrogen energy.

These conclusions collectively emphasize a shared positive perspective on hydrogen energy between Poland and Germany, with notable differences in awareness, education, information sources, and perceptions of challenges and advantages. The results highlight opportunities for policy alignment, educational initiatives, and strategic investments in both countries to foster the development and adoption of hydrogen energy.

The present study, while comprehensive in its comparative analysis of hydrogen technologies in Poland and Germany, exhibits certain limitations. Primarily focused on policy-level aspects, the research may overlook grassroots challenges and localized barriers in the implementation of hydrogen technologies. Moreover, the multidimensional framework, although extensive, may not capture all relevant variables such as local governance or community engagement. Despite these limitations, the research offers novel insights into the role of hydrogen technologies in sustainable development. It highlights the need for frameworks that consider not just the technological but also the socio-economic and political facets of energy transformation. These findings hold significant implications for policy decisions and strategic planning in the broader field of energy and environmental studies. The information gathered can serve as a foundational element for future research and inform the development of more comprehensive sustainable energy models. These observations align closely with the

survey results presented, indicating a strong preference for sustainable technologies like hydrogen in energy strategies. The study thus holds both theoretical and practical implications, most notably the need for an integrated policy approach that acknowledges the interplay of technological, economic, and social factors.

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