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HYDROGEN AS AN ENERGY SOURCE AND AS A FORM OF ENERGY STORAGE

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ABSTRACT: That paper explores the production and utilisation of clean hydrogen as a sustainable energy source, with a focus on the storage of hydrogen in underground caverns. The purpose is to assess the feasibility and benefits of using hydrogen as a clean energy alternative, particularly through large-scale storage solutions. The methodology involves a detailed review of current hydrogen production techniques, such as electrolysis using renewable energy, and the geological and technical aspects of cavern storage. The findings indicate that while hydrogen production is becoming increasingly efficient, cavern storage offers a viable solution for managing supply and demand, ensuring energy security. Practical implications include the potential for large-scale energy storage, enhancing grid stability, and supporting the transition to a low-carbon economy. Social implications involve reducing greenhouse gas emissions and promoting sustainable energy practices. The originality of the paper lies in its integration of hydrogen production and cavern storage, highlighting their combined potential for a sustainable energy future.

KEYWORDS: hydrogen, RES, green energy, energy storage

Introduction

This article fills a gap in the existing literature by integrating two key, yet often separately examined issues: the production of clean hydrogen and its storage. While previous studies have typically focused on one of these aspects—either on production technologies or storage methods—this paper offers a comprehensive perspective that takes into account technological, environmental, and practical dimensions. The article makes a significant contribution to the development of an integrated approach to the challenges related to hydrogen production and storage. The article contributes to expanding the current state of knowledge in the following key areas: (I) clean hydrogen production (II) different technologies of hydrogen production and their storage (III) and (IV) salt cave storage.

The production of clean hydrogen and its efficient storage are key components in global efforts to combat climate change and drive the energy transition. In the face of growing demand for sustainable energy sources, hydrogen produced using renewable energy sources (RES) is gaining importance as one of the most critical energy carriers of the future. The production of clean hydrogen, particularly through the electrolysis of water using renewable energy, offers the potential for significant reductions in greenhouse gas emissions, contributing to the achievement of climate goals set by international agreements. The key ideas about clean energy and hydrogen can be effectively presented using the diagram:

Need for Sustainable Energy → Green Hydrogen via RES → Reduction or elimination of Carbon Emissions.

This direction of decarbonisation is supported by (I) Paris Agreement Goals, (II) Energy Transition and (III) the Decarbonised Economy.

However, the production of hydrogen is only half the battle. A key aspect is the ecological and clean production of hydrogen, known as green hydrogen production. Green hydrogen is produced by electrolysing water using energy from renewable sources such as solar, wind, or hydro power. In this process, water is split into hydrogen and oxygen without emitting carbon dioxide, making it a crucial element in the pursuit of a zero-emission economy. Green hydrogen has the potential to replace fossil fuels in various sectors, significantly reducing greenhouse gas emissions.

To ensure hydrogen's effective and scalable use, appropriate storage and handling methods must be provided. As a low-density gas, hydrogen requires innovative storage solutions that allow it to be stored in large quantities with minimal loss. Traditional storage methods, such as compression or liquefaction, are costly and energy-intensive. Consequently, there is increasing attention on modern hydrogen storage technologies, such as underground salt caverns. These natural geological formations offer vast capacities for storing hydrogen under high pressure, while also providing a high level of safety. This approach not only enhances storage efficiency but also allows for flexible adaptation to fluctuating energy demands, which is crucial for integrating renewable energy sources. As a result, effective hydrogen storage is an integral part of developing hydrogen infrastructure, enabling the full potential of hydrogen as a clean energy carrier on a global scale.

Research methods

The research methodology applied in this study, which focuses on the production of clean hydrogen and its storage methods, is based on an in-depth analysis of secondary research. This approach enables a comprehensive understanding of the current state of knowledge in hydrogen technologies, as well as the challenges and opportunities associated with their development. By conducting an analysis of scientific literature, industry reports, and available technological data, it becomes possible to identify key trends and innovations shaping the advancement of hydrogen technologies.

One of the most significant advantages of using secondary research is the access to a broad range of sources, offering diverse perspectives and data collected from studies conducted worldwide. This allows for a more complete picture not only of current technological achievements but also of the challenges and issues related to the production and storage of clean hydrogen. It also enables the identification of technological gaps that may hinder further development in this field and provides insight into which technologies might be most effective in different geographical and economic contexts.

This method is also highly efficient in terms of time and cost. It avoids the need for expensive primary research while still granting access to existing data and analyses that can be incredibly valuable to researchers. Secondary research allows for the comparison of different technologies and approaches used in various contexts, which in turn helps identify best practices and barriers to the broader implementation of hydrogen technologies.

Furthermore, the results obtained from such analysis can serve as a valuable source of knowledge for policymakers dealing with hydrogen and zero-emission economy issues. Through a comprehensive and critical evaluation of existing solutions and the identification of key trends, policymakers can develop more effective strategies for implementing hydrogen technologies at both the national and international levels. The insights gained can also support the formulation of public policies that promote the development of hydrogen technologies, thereby facilitating the achievement of climate goals and sustainable development. This approach not only supports the advancement of innovative technologies but also ensures their effective integration with existing energy systems, which is crucial for meeting global targets related to greenhouse gas emissions reduction.

An overview of the literature

This section of the article will focus on a literature review, discussing key sources and industry reports. The aim is to present the current directions in the development of technologies related to the production of clean hydrogen and its storage methods. The analysis of the literature allows for the identification of the latest achievements, trends, and innovations in this field, as well as highlighting the technological and economic challenges that significantly impact the further development of the hydrogen sector. Reviewing the available studies and reports provides a foundation for understanding how the landscape of hydrogen production and storage is evolving, and which technologies hold the greatest potential in the context of global efforts towards decarbonisation and sustainable development.

Hydrogen Production

Hydrogen can be used to reduce CO_2 emissions, but to achieve full decarbonisation, it is crucial to consider the source of hydrogen. Hydrogen production, a key element in the energy transition, can be classified into three main groups, each characterised by different approaches to raw materials and technology (Borowski, 2024). The first group includes hydrogen production based on renewable energy. This method of hydrogen production, often referred to as “green hydrogen,” uses water electrolysis powered by renewable energy sources such as solar, wind, or hydropower (SES Hydrogen, 2024). This method of hydrogen production can be schematically presented as follows:

Green H_2: Renewable Energy → Electrolysis → Green Hydrogen.

Through this process, hydrogen can be produced without greenhouse gas emissions, making it a key component in the pursuit of a zero-emission economy. In addition to electrolysis, green hydrogen can also be produced through steam reforming of biomethane, pyrolysis of biogenic feedstocks, and water photolysis—a method that uses solar energy to split water molecules into hydrogen and oxygen. This can occur through photocatalysis, involving semiconductor materials activated by sunlight. Although this technology is still in the research phase, its major advantage lies in the direct use of solar energy—the most accessible source of renewable energy—for the production of clean hydrogen (Hassan et al., 2024; Domenighini et al., 2024).

The second group involves hydrogen production based on coal gasification and natural gas, often supported by carbon capture and storage (CCS) systems. This type of production, also known as “blue hydrogen,” involves converting fossil fuels into hydrogen while capturing and storing the resulting carbon dioxide. This method of hydrogen production can be schematically presented as follows:

Blue H_2: Natural Gas → Pipeline → Steam Reforming → CO_2 Capture → Blue Hydrogen.

Although this method still involves CO_2 emissions, CCS systems can significantly reduce its environmental impact, making the process more climate-friendly (Borowski & Karlikowska, 2023).

The third group is hydrogen production based solely on fossil fuels, primarily through steam methane reforming or coal gasification, mainly without the application of CCS technology. This type

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of production, known as "gray/black hydrogen," is the most common and also the least environmentally friendly way of producing hydrogen.

This method of hydrogen production can be schematically presented as follows:

Gray/Black H_2: Coal Gasification → Gas Cleanup → Hydrogen Separation → CO_2 Capture (optional) → Gray/Black Hydrogen.

The emissions associated with this process are significant, raising questions about its long-term viability in the context of global emission reduction goals (Dash et al., 2023). High-emission hydrogen produced from fossil fuels generates substantial amounts of carbon dioxide—when produced from natural gas, approximately 10 tons of CO_2 are emitted for every ton of hydrogen produced. However, it should be noted that according to current forecasts, lower-carbon hydrogen, while more environmentally friendly, is significantly more expensive to produce (Lambert et al., 2024).

Each of these groups plays a crucial role in the current landscape of hydrogen production, but only sustainable methods based on renewable energy sources offer the prospect of a truly zero-emission future (Acar & Dincer, 2019). On a global scale, only a negligible portion of hydrogen production can currently be classified as zero-emission. The vast majority of hydrogen is still produced from conventional, high-emission sources, which has a significant impact on greenhouse gas emissions and moves us further from achieving global climate goals. To illustrate this division, the following figure presents the detailed share of hydrogen production from different sources at the end of 2021, showing the extent to which various technologies contribute to carbon dioxide emissions (Figure 1).

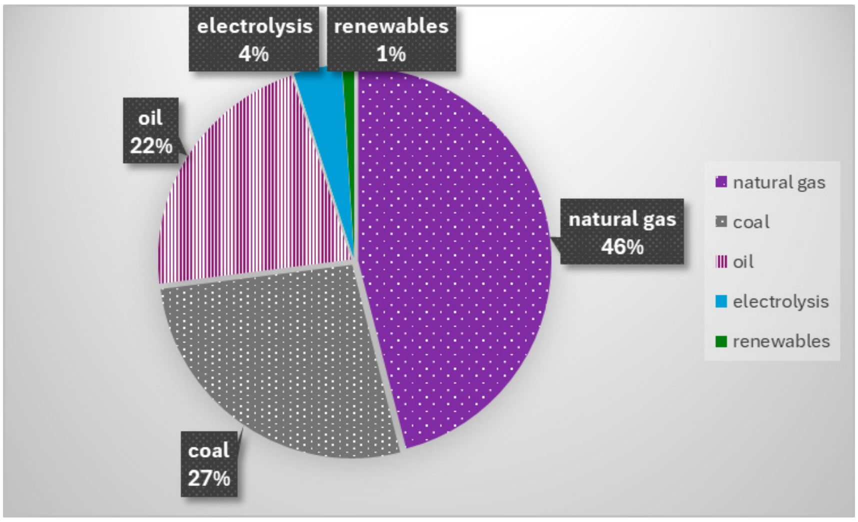

Figure 1. Global hydrogen production by source

Source: author's work based on IRENA (2024).

In addition to hydrogen production via electrolysis, steam reforming of biomethane, pyrolysis of biogenic feedstocks, or water photolysis, hydrogen can also be produced through other methods. In biological processes, it is generated by microorganisms such as anaerobic bacteria or microalgae through natural metabolic reactions. One example is dark fermentation, in which bacteria break down organic matter without the presence of light, producing hydrogen as a by-product (Ahmad et al., 2024; Topkar et al., 2025). Another possibility is biological photosynthesis, where certain microorganisms use sunlight to split water and generate hydrogen. This method of hydrogen production can be schematically presented as follows:

Organic matter → Anaerobic bacteria/microalgae → Metabolic reactions → Dark fermentation or Biological photosynthesis → Hydrogen (H_2).

Hydrogen can also be obtained through thermochemical biomass processing, which involves breaking down biomass at high temperatures, usually with limited oxygen supply (e.g., through gasification), to produce synthesis gas—a mixture containing hydrogen, carbon monoxide, and methane. Hydrogen can then be separated from this mixture using various techniques, such as adsorption or membrane separation (Alvarado-Flores et al., 2024; Rauch et al., 2024). This is an efficient method

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of producing hydrogen from renewable feedstocks, including plant or forest waste. This method of hydrogen production can be schematically presented as follows:

Biomass (e.g. plant waste) → High temperature + limited oxygen → Gasification → Synthesis gas (H_2 + CO + CH_4) → Separation (adsorption / membranes) → Hydrogen (H_2).

Hydrogen Storage

Hydrogen storage technologies have emerged as a promising pathway to achieving sustainable energy development (Osman et al., 2024). Utilising hydrogen to meet energy demands, reduce greenhouse gas emissions, and support innovations in clean energy holds immense potential. Underground hydrogen storage represents a particularly promising approach for efficiently managing large quantities of this gas, offering significant advantages in terms of safety and spatial efficiency (Muhammed et al., 2022). Salt caverns are especially favoured due to their beneficial properties, such as low permeability and extensive storage capacity. These features provide substantial buffer capacity, making them an ideal solution for storing intermittent energy sources (Tarkowski & Uliasz-Misiak, 2022). In the case of underground hydrogen storage, salt caverns offer the most promising option due to their low investment costs, high sealing potential, and minimal requirements for cushion gas, which plays a crucial role in maintaining necessary pressure within the storage tank (Caglayan et al., 2020). One of the key functions of cushion gas is to act as a buffer, ensuring that storage pressure remains within the desired range despite fluctuations in hydrogen demand or supply (Prigmore et al., 2024).

Results and discussion of the research

Increasing the share of energy produced from renewable energy sources (RES) in the energy balance presents not only a technological and environmental challenge for Poland but also for most developed economies around the world. Globally, investments in clean energy are steadily rising. This trend is driven by both growing environmental awareness and the need to address climate change. Figure 2 illustrates the magnitude of financial investments in clean energy compared to fossil fuels.

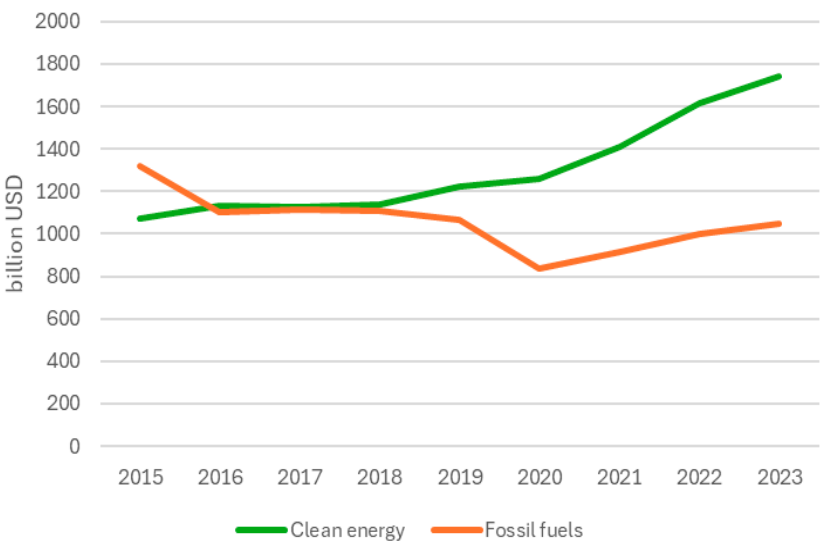

Figure 2. Investment in green energy and fossil fuels in billions of USD from 2015 to 2023

Source: author's work based on IEA (2024).

Many countries are taking ambitious actions to reduce their dependence on fossil fuels and increase the share of renewable energy sources (RES) in their energy mixes. The pursuit of sustainable development not only necessitates the introduction of advanced technologies but also requires the implementation of appropriate policies and regulations that support the growth of the RES sector. These investments not only contribute to reducing greenhouse gas emissions but also stimulate the development of new economic sectors, creating jobs and promoting technological innovations.

A key limitation to the dynamic growth of renewable energy sources remains the underdeveloped infrastructure for large-scale energy storage and balancing services for power systems, which are essential for ensuring stability and security of electricity supply (Czepło & Borowski, 2024). This issue is particularly significant due to the nature of RES production, which is highly dependent on weather conditions and therefore unstable. For instance, wind and solar energy, which constitute a significant part of the energy mix in many countries, exhibit substantial variability in production throughout the day and across different seasons. A lack of wind or sunlight leads to sudden drops in energy production, which can cause severe disruptions in the power system if appropriate measures are not taken.

The instability of RES production poses serious challenges for power system operators, who must maintain a balance between supply and demand for energy at all times. When RES production exceeds demand, it is crucial to store excess energy efficiently so that it can be used later when production falls below demand. Therefore, the development of energy storage systems becomes a critical element in supporting an unstable RES-based system.

Energy storage solutions such as lithium-ion batteries, hydrogen storage technologies, and pumped hydro storage allow for the storage of excess electrical energy produced during periods of surplus and its return to the grid when needed (Sauhats et al., 2016). This capability helps mitigate the effects of RES production instability and ensures continuity of energy supply, which is essential for the functioning of modern economies. In the long term, effective energy storage systems will be crucial for integrating increasing amounts of RES into the energy mix, enabling the achievement of ambitious decarbonisation and energy transition goals.

In this context, hydrogen, as an innovative technological solution, can play a key role. Serving as an efficient energy storage medium, hydrogen has the potential to significantly support processes aimed at achieving climate neutrality. By storing excess energy produced by RES and utilising it during times of increased demand, hydrogen becomes a central element in global and European energy strategies, providing an innovative response to the challenges associated with energy transition.

Hydrogen, as an energy carrier, can be used for energy storage processes, offering innovative solutions to the challenges associated with the instability of RES production. Hydrogen can be produced through water electrolysis using excess electrical energy generated by RES during periods of low demand. The stored hydrogen can then be used in various ways: converted back into electricity using fuel cells, burned in gas turbines for energy production, or utilised in industry, transportation, or heating. This capability not only enables long-term energy storage but also offers flexibility in its later use, making hydrogen a key element in the decarbonisation and energy transition process.

Energy storage can be a crucial aspect of hydrogen strategies, as efficient development of hydrogen storage systems or its production at RES sites can significantly support the regulation of the national power system. Ensuring electrical security in systems based on renewable sources requires the development of energy storage systems, and hydrogen application is a necessary component of this strategy. The report "Green Hydrogen from RES in Poland" confirms that planned initiatives for the coming years offer many benefits but cannot ensure the stability of the National Power System (PSEW, 2024). Technological development will enable the effective use of hydrogen for energy storage in the future. Examples of hydrogen storage in underground reservoirs include pilot projects in Germany.

Energy service provider EWE[1] is exploring the possibilities of underground hydrogen storage in Rüdersdorf as part of the HyCAVmobil research project. The project aims to use hydrogen as an energy storage medium, allowing for flexible and environmentally friendly energy use. Storage takes place in a large underground cavernous salt dome in Rüdersdorf, Brandenburg, where 6 tons of hydrogen can be stored. If tests are successful, industrial-scale storage in caverns, which provide a safe and efficient solution for hydrogen storage, will begin (EWE, 2024). Cavernous storage allows for large quantities of hydrogen to be stored and introduced into the energy system as needed. The diagram of cavernous storage cavities is shown in Figure 3.

[1] EWE is a German company operating in the fields of energy, telecommunications, and information technology in Lower Saxony.

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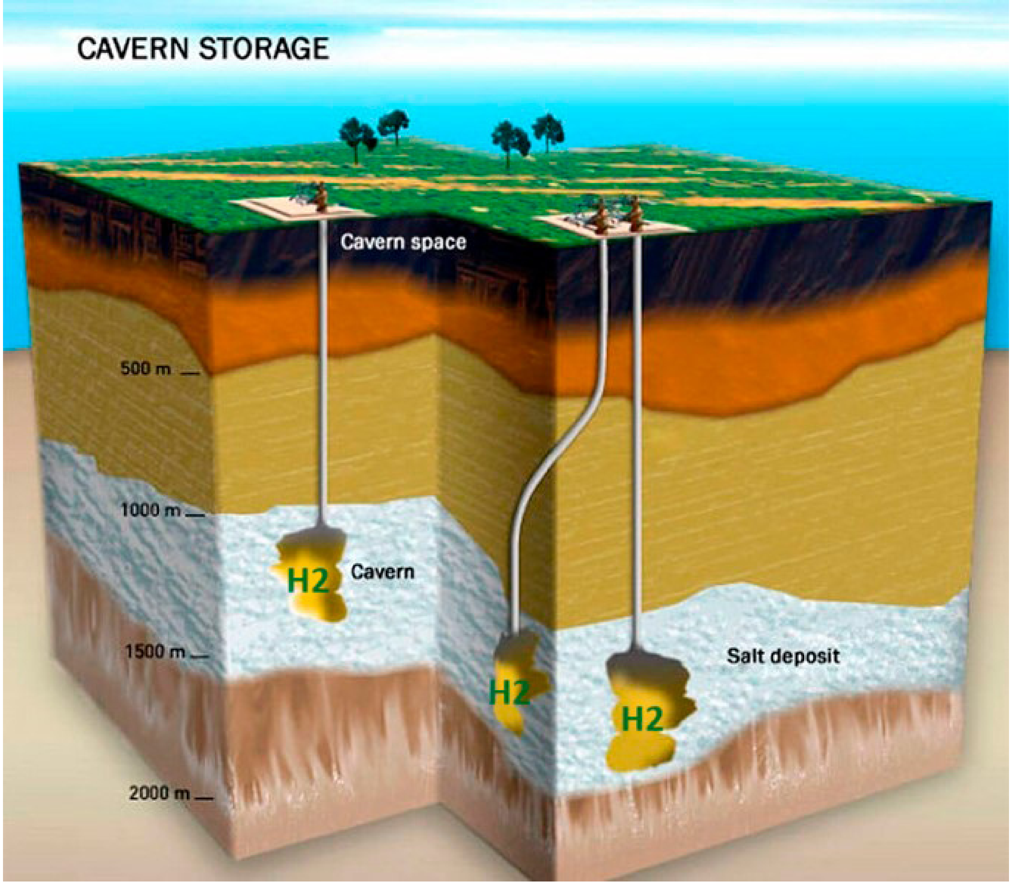

Figure 3. Diagram of a salt cavern for hydrogen storage
Source: author's work based on Fletcher A. et al. (2024).

To safely store hydrogen in salt caverns, a thorough geological assessment of the area becomes crucial. This would ensure stable renewable energy supplies even when wind and solar sources temporarily provide less energy. The experiences from Rüdersdorf may prove pivotal for future hydrogen economy projects and significantly contribute to the development of sustainable energy storage solutions. Similar initiatives are also being pursued in other parts of Europe, including Northern Ireland. The engineering firm Harland & Wolff has presented research results that highlight the immense potential of storing hydrogen in salt caverns in this region. The project, which involves creating seven salt caverns in County Antrim, aims to develop infrastructure capable of storing up to 500 million cubic meters of gas (Donaldson, 2023). This ambitious endeavour not only supports the advancement of hydrogen storage technology but also has the potential to significantly stabilise energy supplies as the share of renewable energy sources in the energy mix increases. These examples demonstrate that European hydrogen storage projects hold substantial potential, which could accelerate the energy transition and support the achievement of climate goals on the continent.

European Geological Potential for Hydrogen Storage

Salt deposits in Europe represent strategically important geological resources that could play a key role in a future hydrogen-based economy. In the era of energy transformation aimed at reducing greenhouse gas emissions and gradually moving away from fossil fuels, hydrogen is becoming one of the most crucial energy carriers. However, to fully realise its potential, adequate storage methods are necessary. In this context, salt caverns – natural or artificially created spaces in salt deposits – could become a critical component of hydrogen infrastructure. Almost all hydrogen could be stored in salt caverns, utilising the vast geological potential across Europe (Neumann et al., 2023). Europe boasts numerous and extensive salt deposits, ranging from the northwestern part of the continent through Germany, the Netherlands, Poland, to the southern regions such as the Mediterranean basin. One of

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the most well-known and utilised areas is northern Germany, where salt deposits have been used for years to store gases such as methane. The Lower Saxony region, particularly around Hanover and Oldenburg, is an example of where the potential of salt caverns is already being used for industrial purposes and could now be adapted for hydrogen storage.

Another significant area is Poland, which has rich deposits of rock salt, especially in the Kujawy and Wielkopolska regions. The salt mines in Inowrocław and Kłodawa could potentially be converted into hydrogen storage facilities in the future, supporting the national energy system in the context of increasing shares of renewable energy sources (RES). Hydrogen stored in these caverns could be used during periods of high energy demand or when RES production declines, ensuring energy supply stability.

In the Netherlands, where the geological space beneath the North Sea is used for natural gas storage, future plans also include hydrogen storage in salt caverns. The development of technology in this area would further enable the use of offshore wind energy, which could provide energy for water electrolysis and hydrogen production, followed by storage in salt deposits.

In southern Europe, particularly in the Mediterranean basin, there are also favorable geological conditions for creating salt caverns. Although this region is less developed in terms of gas storage, it has significant potential that could be harnessed in the coming decades.

Salt caverns are characterised by exceptional impermeability and geological stability, making them ideal for hydrogen storage. Salt, as a geological material, has the ability to self-seal, which further enhances the safety of gas storage (Minougou et al., 2023). Additionally, storing hydrogen in salt caverns allows for gas storage at high pressure, which increases the efficiency of the available space.

In the context of European climate policy, the development of hydrogen storage technology in salt caverns is becoming a priority. The European Union aims to create an integrated hydrogen infrastructure network that will allow for the free flow of this energy carrier between member states. Salt caverns could serve as strategic nodes in this network, enabling the storage of large quantities of hydrogen and its distribution based on the energy needs of different regions.

The distribution of salt deposits in Europe from various geological eras, with the location of the Rüdersdorf test cavern marked, is illustrated in the Figure 4.

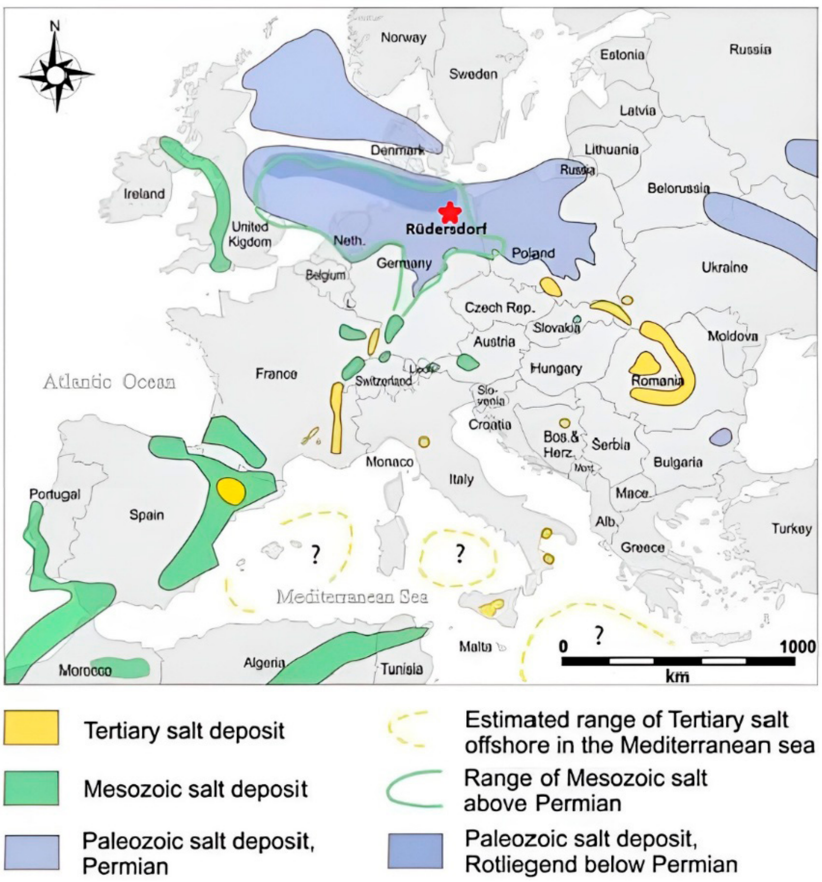

Figure 4.
Distribution of salt deposits in Europe from various geological eras
Source: Scottish (2024).

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Salt deposits in Europe have enormous potential that can be leveraged within the context of the emerging hydrogen economy. Salt caverns offer unique solutions for the safe and efficient storage of hydrogen, which is crucial for the stability of future energy systems based on renewable sources. European salt resources, stretching from the northern to the southern regions of the continent, represent strategic assets that can support the energy transition and contribute to achieving climate goals in Europe.

Conclusions

The findings from the conducted research highlight several key trends and dependencies in the field of energy technology development. Firstly, the global increase in investments in clean energy reflects the growing environmental awareness and the need to combat climate change. However, while renewable energy sources are making up an increasing share of the global energy mix, they are characterised by production instability. Therefore, there is an urgent need to develop effective energy storage systems.

Hydrogen emerges as a crucial solution in this context, both as a source of clean energy and as an efficient energy storage medium that can balance fluctuations in energy supply from renewable sources. Modern technologies enable the storage of hydrogen in underground salt caverns, representing a promising research direction. These caverns offer a safe and spatially efficient means of storing hydrogen on a large scale, which can significantly impact the stability of energy grids based on renewable sources. This innovative trend has the potential to play a key role in the future of the global zero-emission economy.

The scientific aim of this work was to investigate the processes of hydrogen production and storage as a pathway to achieving zero or low emissions. The focus of the research was to identify and analyse innovative actions undertaken by companies within the energy sector to advance clean energy technologies. By exploring both technological advancements and strategic implementations, this study contributes to the existing body of knowledge on emission reduction by highlighting novel and practical solutions that support the global energy transition toward sustainability.

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HYDROGEN JAKO ŹRÓDŁO ENERGII ORAZ JAKO FORMA MAGAZYNOWANIA ENERGII

STRESZCZENIE: Artykuł dotyczy badań związanych z produkcją i wykorzystaniem czystego wodoru jako zrównoważonego źródła energii, koncentrując się na magazynowaniu wodoru w podziemnych kawernach. Celem jest ocena wykonalności i korzyści płynących z wykorzystania wodoru jako alternatywnego źródła czystej energii, szczególnie poprzez rozwiązania magazynowania na dużą skalę. Metodologia obejmuje szczegółowy przegląd obecnych technik produkcji wodoru, takich jak elektroliza przy użyciu energii odnawialnej, oraz aspektów geologicznych i technicznych związanych z magazynowaniem w kawernach. Wyniki wskazują, że chociaż produkcja wodoru staje się coraz bardziej efektywna, magazynowanie w kawernach oferuje realne rozwiązanie w zarządzaniu podażą i popytem, zapewniając bezpieczeństwo energetyczne. W praktyce oznacza to potencjał dla magazynowania energii na dużą skalę, zwiększenie stabilności sieci oraz wsparcie w przejściu na gospodarkę niskowęglową. Społeczne implikacje obejmują redukcję emisji gazów cieplarnianych i promowanie zrównoważonych praktyk energetycznych. Oryginalność artykułu polega na integracji produkcji wodoru i magazynowania w kawernach, podkreślając ich połączony potencjał na rzecz zrównoważonej przyszłości energetycznej.

SŁOWA KLUCZOWE: wodór, OZE, zielona energia, magazyny energii

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