

Review

The Development, Current Status and Challenges of Salt Cavern Hydrogen Storage Technology in China

Jun Huang^{1,2}, Xinbo Ge^{1,**} , Hongling Ma² , Xilin Shi^{2,*}  and Yinpeng Li²

¹ College of Energy and Mining Engineering, Shandong University of Science and Technology, Qingdao 266590, China; huangjun_lmn@163.com

² State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China; hlma@whrsm.ac.cn (H.M.); ypli@whrsm.ac.cn (Y.L.)

*,** Correspondence: xlshi@whrsm.ac.cn (X.S.); gexinbo@163.com (X.G.)

Abstract: This paper provides a systematic visualization of the development, current status and challenges of salt cavern hydrogen storage technology based on the relevant literature from the past five years in the Web of Science Core Collection database. Using VOSviewer (version 1.6.20) and CiteSpace software (advanced version 6.3.R3), this study analyzes the field from a knowledge mapping perspective. The findings reveal that global research hotspots are primarily focused on multi-energy collaboration, integration of renewable energy systems and exploration of commercialization, highlighting the essential role of salt cavern hydrogen storage in driving the energy transition and promoting sustainable development. In China, research mainly concentrates on theoretical innovations and technological optimizations to address complex geological conditions. Despite the rapid growth in the number of Chinese publications, unresolved challenges remain, such as the complexity of layered salt rock, and thermodynamic coupling effects during high-frequency injection and extraction, as well as issues concerning permeability and microbial activity. Moving forward, China's salt cavern hydrogen storage technology should focus on strengthening engineering practices suited to local geological conditions and enhancing the application of intelligent technologies, thereby facilitating the translation of theoretical research into practical applications.

Keywords: energy storage; salt cavern hydrogen storage; knowledge mapping; visualization; technological challenges



Academic Editor: Alberto Pettinau

Received: 22 December 2024

Revised: 13 February 2025

Accepted: 19 February 2025

Published: 21 February 2025

Citation: Huang, J.; Ge, X.; Ma, H.; Shi, X.; Li, Y. The Development, Current Status and Challenges of Salt Cavern Hydrogen Storage Technology in China. *Energies* **2025**, *18*, 1044. <https://doi.org/10.3390/en18051044>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

According to the United Nations, the global population has reached 8 billion, marking an important milestone in human development [1]. It is projected that by 2030, the world's population will increase to 8.5 billion, rising further to 9.7 billion by 2050 and reaching 10.4 billion by 2100 [2]. As one of the most populous countries in the world, China has a population of approximately 1.4 billion, accounting for nearly 18% of the global population. The resource consumption and environmental pressure resulting from population growth have led to increased societal focus on sustainable development. Hydrogen energy storage, as a zero-emission energy source, offers advantages such as high energy density, large storage capacity and seasonal storage, making long-duration hydrogen storage critical for reducing carbon emissions and improving air quality [3]. China aims to peak carbon emissions by 2030 and achieve carbon neutrality by 2060, and the development of hydrogen storage technology will play a key role in achieving these goals [4].

In the face of growing energy demand and environmental pressures, China must accelerate the development of hydrogen storage technologies to enhance their efficiency, safety and economic viability. This includes breakthroughs in new technologies such as underground hydrogen storage (UHS), high-pressure hydrogen storage, liquid hydrogen storage and solid-state hydrogen storage [5]. In 2022, the National Development and Reform Commission and the National Energy Administration jointly issued the “Hydrogen Energy Industry Development Mid- and Long-term Plan (2021–2035)”, which outlines hydrogen energy as a key component of the future national energy system, an important carrier for the green and low-carbon transformation of energy end-use and a strategic emerging industry for future development [6]. In November 2024, the 12th meeting of the Standing Committee of the 14th National People’s Congress passed the “Energy Law of the People’s Republic of China”, which encourages and supports the development of hydrogen energy, energy storage and other key and cutting-edge technologies for research, application and industrialization [7].

Hydrogen gas has characteristics such as low density, small energy storage per unit volume, and flammability, making the safe and efficient storage and transportation of hydrogen a significant challenge [8]. The feasibility of achieving safe and efficient hydrogen storage and transportation will directly affect the large-scale and commercial application of hydrogen energy [9]. Currently, various hydrogen storage technologies are under development and application [10], as illustrated in Figure 1. The ability to achieve large-scale, seasonal energy storage is a critical factor in evaluating the future potential of hydrogen storage technologies [11]. However, surface hydrogen storage faces limitations such as limited storage capacity and high costs, making it difficult to meet the demands for large-scale and long-term storage [12]. In contrast, UHS offers significant advantages, including large-scale storage, low cost, long storage cycles, high safety and seasonal storage capabilities, making it a promising solution for hydrogen storage [13]. Among these, salt cavern hydrogen storage is regarded as one of the most promising geological storage solutions due to its large scale, good sealing performance, low buffering gas requirements, high operational pressure, and high injection and extraction efficiency [14]. Table 1 presents the operational parameters of the four salt cavern hydrogen storage sites currently in operation worldwide [15]. Research on UHS in China lags behind and while there is no completed UHS project, a large-scale deep-salt cavern hydrogen storage project in Pingdingshan, Henan, Asia’s first, is currently underway [16]. Compared with international salt dome storage projects, China’s salt cavern construction sites are primarily composed of continental layered salt rock, which presents challenges such as low salt layer quality, numerous interlayers, and high insoluble content, leading to difficulties in cavity formation and low efficiency [17]. However, China’s abundant and widely distributed salt resources offer significant potential and development space for salt cavern hydrogen storage, gas storage, and other underground energy applications [18]. Figure 2 illustrates the distribution of salt mines in China. Storing hydrogen in underground salt cavern can help address the uneven distribution of energy resources in China and promote the large-scale and rapid development of the hydrogen energy industry [19].

Table 1. Global operating salt cavern hydrogen storage projects.

Project Name	Operating Conditions/MPa	Depth/Meters	Capacity/m ³
Teesside (UK)	4.5	365	210,000
Clemens (USA)	7–13.7	1000	580,000
Moss Bluff (USA)	5.5–15.2	1200	566,000
Spindletop (USA)	6.8–20.2	1340	906,000

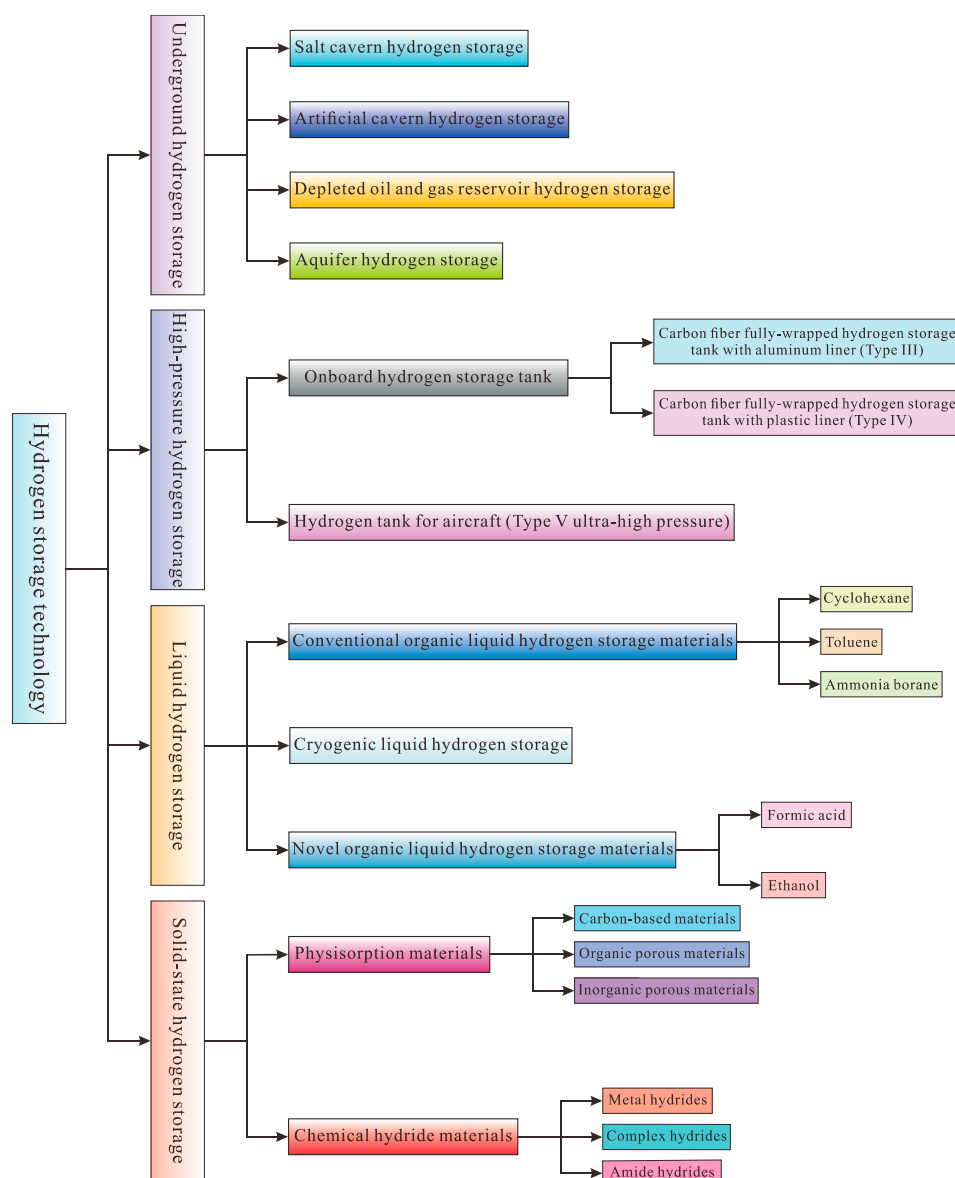


Figure 1. Schematic diagram of different hydrogen storage technologies.

Based on this, this paper employs a scientific knowledge mapping methodology, utilizing VOSviewer and CiteSpace software to conduct a visual analysis of the relevant literature in the field of salt cavern hydrogen storage over the past five years from the Web of Science Core Collection (WOSCC). This study systematically reviews the development and current status of salt cavern hydrogen storage technology, explores the key challenges it currently faces, and discusses potential breakthrough paths for its future development. The aim is to provide scientific support for the large-scale application and high-quality development of hydrogen energy, accelerating the realization of China's "dual carbon" strategy goals.

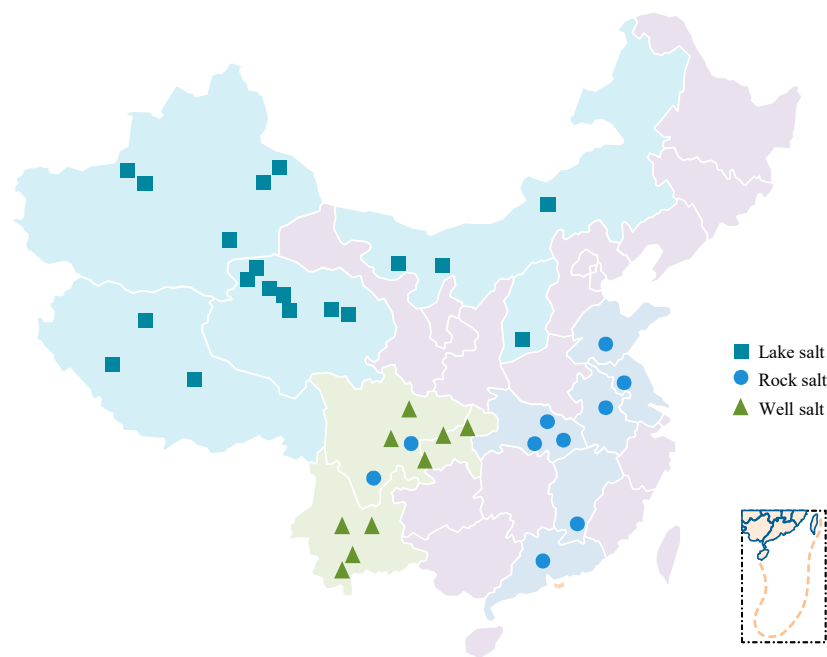


Figure 2. Schematic map of major salt mine distribution in China.

2. Visualization Analysis

2.1. Basic Bibliometric Characteristics

2.1.1. Development of Hydrogen Storage Technologies

Figure 3 shows the development trends of global UHS and the subfield of salt cavern hydrogen storage over the past five years, with statistics as of 18 December 2024. From Figure 3, it can be seen that a total of 601 studies were published in the global UHS field, of which 186 are related to salt cavern hydrogen storage. In China, 43 studies related to salt cavern hydrogen storage were published.

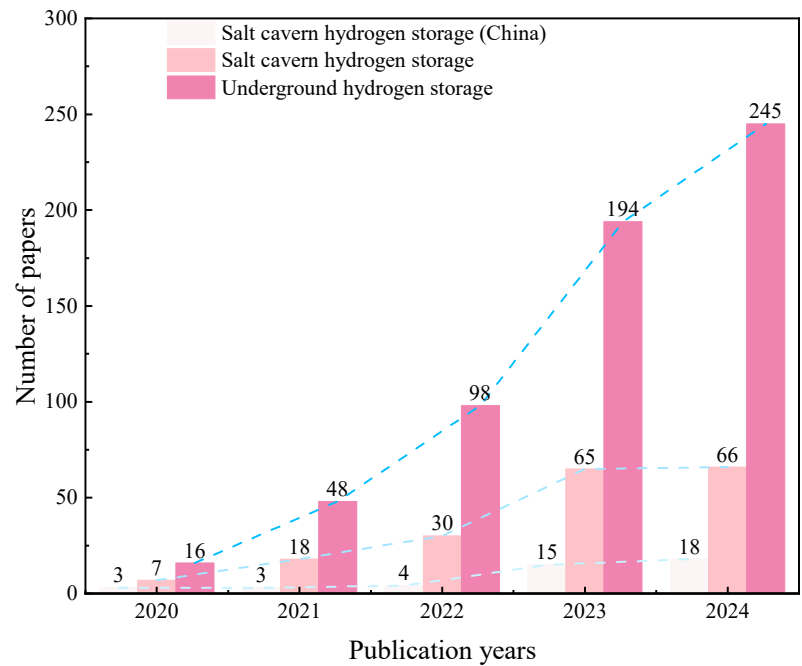


Figure 3. Development trends of UHS and its subfield—salt cavern hydrogen storage.

The number of publications in the global UHS field has shown exponential growth, highlighting that UHS has become an important research direction for achieving large-scale energy storage. This growth trend reflects the urgent need for long-duration and large-scale energy storage technologies in the context of global energy transition and the carbon peak and carbon neutrality goals. As an essential component of UHS, salt cavern hydrogen storage, with its advantages of high sealing performance, large scale and low cost, has attracted increasing research attention year by year [20].

Research on salt cavern hydrogen storage in China started relatively late, with only three related publications in 2020. However, in recent years, research in this field has shown steady growth, with the number of publications reaching 18 in 2024, indicating a gradual increase in research investment and accelerating technological progress.

Although the volume of Chinese publications on salt cavern hydrogen storage lags behind the global level, China has significant development potential in this field, supported by its abundant salt mine resources, favorable policies, and research innovation. The advancement of engineering projects, such as the deep salt cavern hydrogen storage demonstration project in Pingdingshan, Henan, marks a step toward the practical application of salt cavern hydrogen storage technology in China. In the future, with technological innovation and the accumulation of engineering practices tailored to complex geological conditions, China is expected to make breakthroughs in the field of salt cavern hydrogen storage, gradually narrowing the gap with international leading levels.

2.1.2. Analysis of Research Contributions

Figure 4 and Figure 5, respectively, display the international collaboration status and the network of research institutions in the field of salt cavern hydrogen storage over the past five years, from macro and meso perspectives. Each node in the figures represents a country/region or institution and the size of the node reflects the number of publications. Larger nodes indicate higher research output, signifying greater scientific contributions and influence. The lines between nodes represent collaboration between countries/regions or institutions, with line thickness reflecting the intensity of cooperation. Different colors represent different cooperation clusters, with tighter cooperation observed within clusters [21,22].

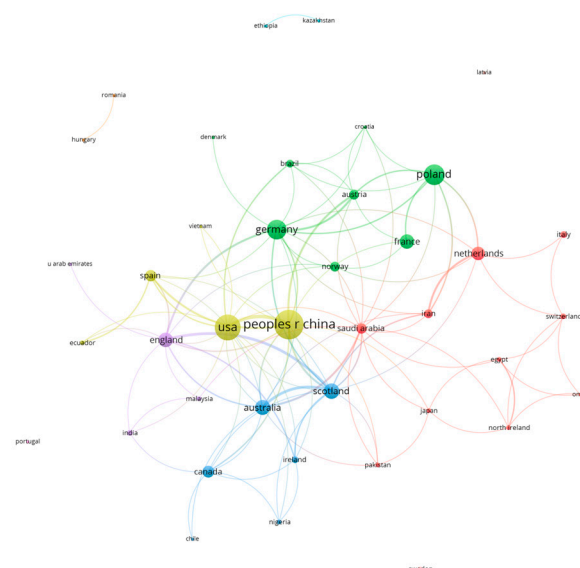


Figure 4. International collaboration network in the field of salt cavern hydrogen storage.

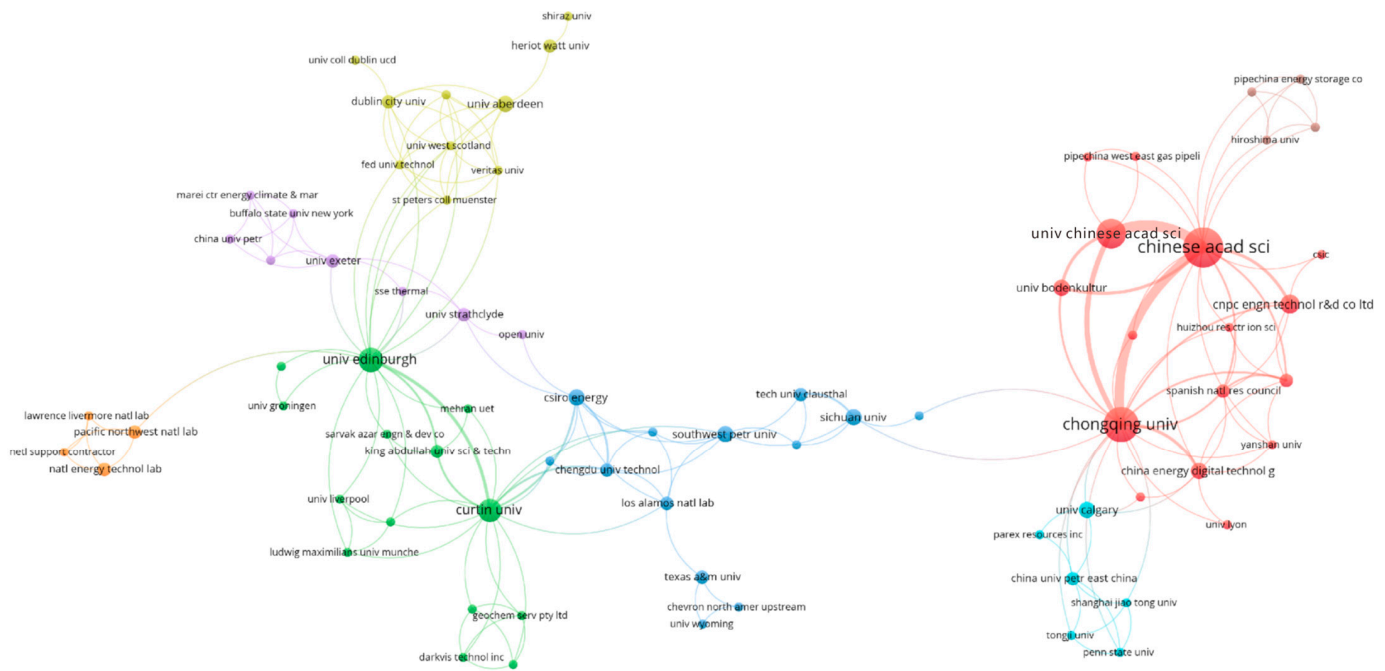


Figure 5. Largest institutional collaboration network in the field of salt cavern hydrogen storage.

From Figure 4, it can be seen that a total of 40 countries/regions have contributed to the publication of research in the field of salt cavern hydrogen storage. The top ten countries/regions by publication volume are as follows: China (43 papers), the United States (35 papers), Poland (24 papers), Germany (22 papers), Scotland (15 papers), Australia (14 papers), England (13 papers), France (13 papers), the Netherlands (12 papers), and Canada (10 papers). China and the United States are the largest nodes in the network, indicating that both countries make the largest scientific contributions and play a leading role in the global research system. In Europe, research on salt cavern hydrogen storage is centered mainly in Germany and Poland, while countries/regions like the Netherlands, Iran and Saudi Arabia are also increasingly integrated into the international research network, reflecting the growing diversity in global salt cavern hydrogen storage research. Notably, China's research collaboration network includes countries/regions such as the United States, Scotland, Austria, Germany, Australia, Canada, England, Spain, and France, indicating China's active participation in international collaborative research and close connections with technologically advanced nations.

From Figure 5, it can be seen that research institutions in different countries/regions have formed several core clusters in the field of salt cavern hydrogen storage, with the cooperation networks among these clusters reflecting the concentration and distribution of research resources. A total of 299 institutions have published papers in this field. The top ten institutions by publication volume are as follows: the Chinese Academy of Sciences (18 papers), Chongqing University (14 papers), the Polish Academy of Sciences (12 papers), the University of Chinese Academy of Sciences (10 papers), the University of Edinburgh (seven papers), Curtin University (six papers), the AGH University of Science and Technology (six papers), China Petroleum Engineering Technology Research Institute (four papers), the University of Alberta (four papers), and the University of Texas in Austin (four papers). In terms of the largest institutional cooperation network, research in China on salt cavern hydrogen storage is mainly concentrated in the Chinese Academy of Sciences and Chongqing University, with the closest collaboration between the two, forming a strong collaborative network with other domestic institutions. However, there is still room for further expansion in cooperation with international core institutions.

Among international institutions, the University of Edinburgh and Curtin University are significant nodes, having established broad cooperation with multiple research institutions worldwide. Despite the Polish Academy of Sciences having a high publication volume in the field of salt cavern hydrogen storage, it is not prominently displayed in the cooperation network due to a lack of direct connections with the largest international institutional clusters.

Overall, the international collaboration network reveals the core positions of countries/regions such as China, the United States and Germany in the field of salt cavern hydrogen storage, as well as the formation of regional research networks centered around Europe and North America. The largest institutional cooperation network further demonstrates that China, led by the Chinese Academy of Sciences and Chongqing University, is rapidly emerging as a key research cluster, showcasing significant development potential. In the future, China can further strengthen its collaboration with core research institutions in Europe and North America, drawing on their experience in salt cavern hydrogen storage technology and engineering practices in regions with similar geological conditions to enhance the development of domestic salt cavern hydrogen storage technology.

2.2. Research Hotspots and Theme Evolution

2.2.1. Analysis of Research Hotspots

Figure 6 presents the keyword co-occurrence network in the field of salt cavern hydrogen storage over the past five years based on the WOSCC database. Each node represents a keyword, with the size of the node reflecting the frequency of its occurrence. The links between nodes indicate the co-occurrence of keywords within the same publications and the thickness of the links represents the strength of their association. Different colors correspond to distinct keyword clusters, reflecting the clustering of research themes. The distribution of nodes, links and colors reveals the research hotspots and their internal associations in the field of salt cavern hydrogen storage [21].

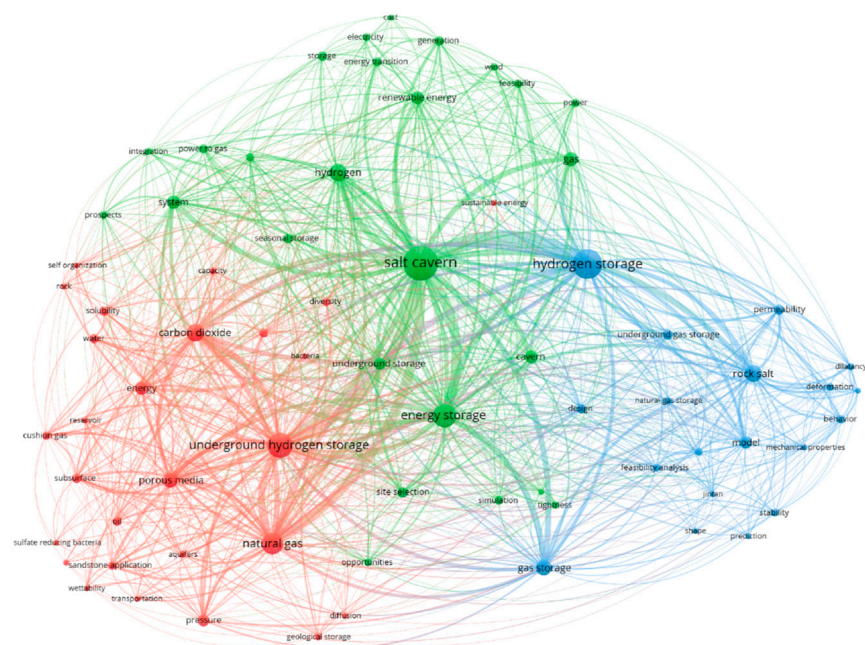


Figure 6. Keyword co-occurrence network in the field of salt cavern hydrogen storage.

From Figure 6, it is observed that the co-occurrence network contains 72 keywords with a threshold of 5, divided into three main clusters representing different research directions. The red cluster focuses on the fundamental applications of UHS and multi-energy

synergy; the green cluster is centered on system optimization in salt cavern hydrogen storage; and the blue cluster addresses the physical properties of rock salt and engineering design. These three clusters are complementary. The top ten keywords by frequency of occurrence are as follows: salt cavern (87 occurrences), hydrogen storage (68 occurrences), UHS (50 occurrences), energy storage (46 occurrences), natural gas (39 occurrences), carbon dioxide (28 occurrences), hydrogen (28 occurrences), rock salt (27 occurrences), gas storage (23 occurrences), and porous media (22 occurrences). Among these, the core keyword salt cavern indicates that salt cavern hydrogen storage is the central focus of the research field, while the high-frequency keyword rock salt highlights that the study of the physical properties of rock salt is fundamental to the development of salt cavern hydrogen storage technology.

The following provides a detailed analysis of the three main clusters:

(1) Red Cluster: “UHS and Energy Synergy Technology”. This cluster’s high-frequency keywords include “UHS”, “natural gas”, “carbon dioxide” and “porous media”. The focus is on exploring the multifunctionality of UHS technology and its synergy with other energy forms.

Salt caverns not only store hydrogen but are also widely used for natural gas storage. Exploring the co-storage technology of hydrogen and natural gas can reduce the cost and technical difficulty of hydrogen storage by utilizing existing natural gas storage facilities. Hibbard et al. [23] assessed the potential of active and abandoned natural gas storage sites in the United States as hydrogen storage facilities. The study found that active natural gas storage sites in the U.S. could store 312 TWh of hydrogen, which would almost meet the hydrogen storage needs of a 100% renewable energy grid. Twenty-three abandoned sites could store 3.9 TWh of hydrogen, making them suitable for seasonal hydrogen storage. Using existing natural gas infrastructure can reduce both economic and technical barriers.

Carbon dioxide, as another underground gas storage research hotspot, shares certain technical similarities with hydrogen storage. Carbon dioxide storage enhances geological sealing capacity through dissolution and mineral reactions, while hydrogen has lower reactivity and smaller losses. The synergistic research between hydrogen storage and carbon dioxide sequestration can provide a more environmentally friendly solution for integrated energy systems. Tayeb et al. [24] investigated the dissolution dynamics of carbon dioxide in salt caverns and aquifers, revealing the impact of diffusion and natural convection on the dissolution rate. Although there are certain similarities in the geological interactions between carbon dioxide and hydrogen (such as gas migration behavior and geological interaction mechanisms), significant differences exist between the two in terms of solubility, storage mechanisms, and leakage risks. In contrast, the underground storage experience with natural gas is more comparable to that of hydrogen, particularly in terms of gas-phase sealing, injection and production strategies, and leakage control. Therefore, future hydrogen storage research should draw more from the engineering practices of natural gas storage rather than directly adopting carbon dioxide storage methods. Tarkowski et al. [25] explored the potential and challenges of underground spaces for storing natural gas, hydrogen and carbon dioxide, noting that hydrogen storage requires further research. While the experience with natural gas and carbon dioxide can be referenced, multi-purpose development may lead to resource conflicts and requires improved legal and planning frameworks. Wallace et al. [26] simulated and compared the storage performance of hydrogen, natural gas and gas mixtures in salt cavern, finding that hydrogen storage shows significant fluctuations and low capacity. They suggested that adjustments to the operating cycle and infrastructure optimization are necessary to reduce structural risks and mixed-gas storage can reduce fluctuations but increases peak pressures and temperatures.

Porous media, such as depleted oil and gas reservoirs and aquifers, are core components of hydrogen storage sites and their porosity characteristics directly influence the hydrogen storage efficiency and leakage risk. Alms et al. [27] studied the geological and infrastructure requirements for underground porous media hydrogen storage in Germany, with a focus on analyzing the storage potential of depleted natural gas reservoirs and aquifers. The study found that sandstone at depths of 800–1100 m, with porosity greater than 20% and permeability greater than 500 mD, is an ideal hydrogen storage formation. Porous media hydrogen storage will become an important component of Germany's future hydrogen infrastructure, meeting industrial hydrogen storage needs and potential hydrogen imports.

(2) Green Cluster: "Salt Cavern Hydrogen Storage and System Optimization". This cluster's high-frequency keywords include "salt cavern", "energy storage", "renewable energy" and "system", with research directions gradually shifting from single-technology development to energy system integration. The frequent co-occurrence of the keywords "renewable energy" and "seasonal storage" indicates that salt cavern hydrogen storage is becoming an important energy storage method for renewable energy sources (such as wind and solar energy), aimed at addressing the intermittency of energy supply.

Takach et al. [28] reviewed the methods of hydrogen production through water electrolysis using renewable energy and its storage in salt cavern, analyzing the potential and economic feasibility of salt cavern hydrogen storage in balancing energy fluctuations. The study compared the advantages and disadvantages of existing technologies, explored the technical challenges, cost issues, and integration constraints of hydrogen production and storage, and pointed out that salt cavern hydrogen storage is one of the most promising energy storage methods in the future, helping to alleviate fluctuations in renewable energy and optimize energy utilization.

The keywords "feasibility" and "system" indicate that researchers are beginning to focus on the economic feasibility assessment of salt cavern hydrogen storage, including investment costs, operational costs and the overall optimization design of energy systems. Kuterbekov et al. [29] explored innovative methods for hydrogen production and storage, with a focus on its integration with renewable energy. The results show that salt cavern hydrogen storage can achieve an efficiency of up to 90%, significantly enhancing grid stability. Epelle et al. [30] reviewed the formation and storage mechanisms of underground hydrogen and natural hydrogen, emphasizing that salt cavern hydrogen storage, due to its safety and high energy density, is the best solution, although challenges related to leakage and cost remain. Natural hydrogen development shows potential but requires further verification of its economic feasibility.

In the rapid injection and extraction processes of hydrogen in salt cavern, pressure and temperature fluctuations may occur, potentially affecting the integrity of the cavern walls and the stability of operations. Liu et al. [31] conducted a pressure optimization simulation for hydrogen storage in layered salt rock with multiple interlayers, providing optimization recommendations for the operation design of deep salt cavern hydrogen storage. The study showed that appropriately increasing the minimum operating pressure can significantly improve rock stability and increasing the injection and production rate can reduce cumulative leakage and improve storage efficiency.

(3) Blue Cluster: "Rock Salt Properties and Engineering Applications". The high-frequency keywords in this cluster include "rock salt", "permeability", "model" and "behavior", with the focus of research on the physical and mechanical properties of rock salt and its engineering applications. These studies provide a solid foundation for the engineering implementation of salt cavern hydrogen storage, particularly for safety assessments and optimization designs under complex geological conditions.

Aftab et al. [32] pointed out that salt caverns are an ideal geological structure for hydrogen storage, offering advantages such as high safety, low permeability and mature technology, but are limited by their relatively low storage capacity. Technical challenges include the impact of microbial activity on pore permeability and the variation in wall thermal stability under pressure and temperature fluctuations. Optimizing operational conditions and addressing these technical challenges are key to improving the efficiency of salt cavern hydrogen storage. Li et al. [33] conducted a stability evaluation and optimization of operational parameters for salt cavern hydrogen storage under high-frequency injection and production conditions. They indicated that both excessively high and low frequencies are detrimental to the stability of hydrogen storage, emphasizing the need for further study of salt rock creep and fatigue effects. Grgic et al. [34] experimentally studied the gas permeability changes in rock salt under different loading conditions, finding that rock salt has a high plasticity and self-healing ability, with limited long-term permeability changes, making it suitable for hydrogen storage in salt cavern. However, the study also highlighted the need to consider the potential impact of transport mechanisms such as hydrogen diffusion on storage safety. Falcon et al. [35] examined the geophysical and transport properties of rock salt and assessed the monitoring potential of seismic and electromagnetic methods in salt cavern development and gas storage. Their experiments showed that the elasticity and permeability of rock salt are linearly related under pressures below 20 MPa and higher pressures can enhance the sealing and mechanical stability of rock salt. This research provides important references for UHS site selection and monitoring, though more extensive data are needed to broaden the applicability of these conclusions. Navaid et al. [36] reviewed the challenges facing UHS, analyzing the suitability of salt caverns, depleted oil and gas reservoirs and aquifers, covering capacity, risks and operational optimization, and providing design and operational recommendations to support large-scale application.

In summary, research hotspots in the field of salt cavern hydrogen storage focus on the synergistic applications of UHS, system optimization and the engineering properties of rock salt. The research shows a trend of combining fundamental research with applied research, as well as balancing system integration with technological innovation, providing theoretical support and practical reference for the future development of large-scale salt cavern hydrogen storage technologies.

2.2.2. Topic Evolution Trend

Figure 7 shows the keyword timeline in the field of salt cavern hydrogen storage over the past five years in WOSCC. The horizontal axis represents time, reflecting the development of different research themes from left to right. Solid lines indicate the active periods of research themes, while dashed lines represent periods of lower popularity. Each node in the figure represents a keyword, with the node size reflecting the frequency of that keyword in the literature. Once a keyword appears, its node is fixed in the year of its first occurrence. Although the keyword may appear again in subsequent years, it is not shown again in the figure. The frequency is increased by 1 in the year of its first occurrence. The lines between nodes indicate that two keywords co-occur in the same document, with the line color reflecting the year of appearance. Betweenness centrality is an indicator used in network analysis to reflect the role of a node as a bridge in the entire network. Nodes with a betweenness centrality of at least 0.1 are highlighted with a purple outer circle, indicating that these keywords play an important bridging role between different research themes. These are key research points or important nodes for knowledge flow across themes in the field [37,38].

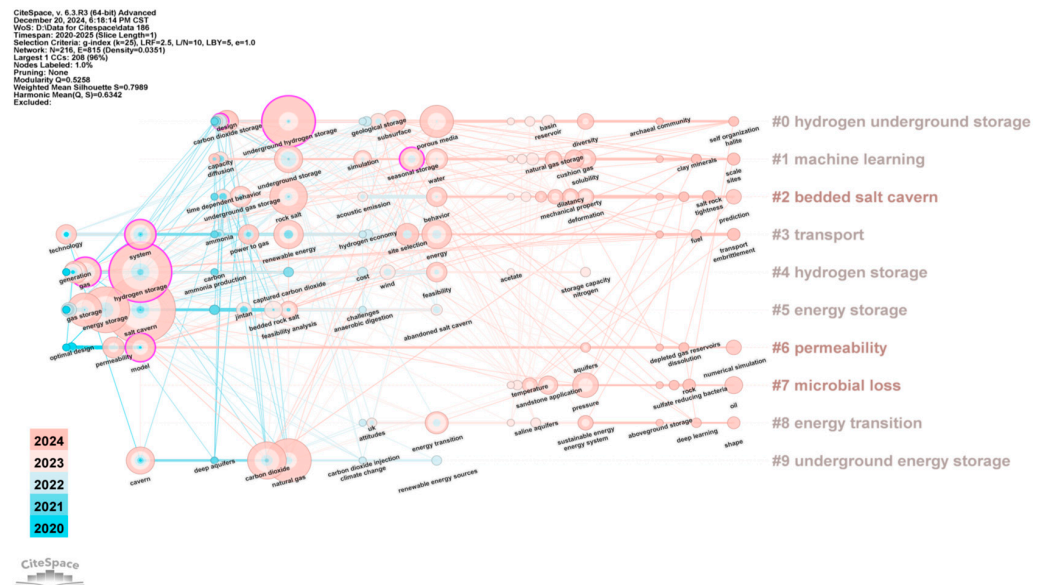


Figure 7. Keyword timeline in the field of salt cavern hydrogen storage.

From Figure 7, the research in the field of UHS in salt caverns can be categorized into 10 major clusters. Each cluster revolves around a specific research focus, with keywords in the same cluster aligned horizontally. The clusters include the following: Cluster #0 “hydrogen underground storage”, Cluster #1 “machine learning”, Cluster #2 “bedded salt cavern”, Cluster #3 “transport”, Cluster #4 “hydrogen storage”, Cluster #5 “energy storage”, Cluster #6 “permeability”, Cluster #7 “microbial loss”, Cluster #8 “energy transition”, and Cluster #9 “underground energy storage”.

Clusters #0, #4, #5, #8 and #9 primarily focus on the multifunctional development and integration of underground energy storage systems, emphasizing the central role of hydrogen in the future energy landscape. These studies aim to enhance energy synergy efficiency and optimize underground storage technologies to promote sustainable energy development, laying the technical foundation for clean energy systems. Chen et al. [39] analyzed the critical role of UHS in achieving China’s carbon peak by 2030 and promoting the development of renewable energy. By integrating geological storage facilities with techno-economic analysis, they identified key UHS sites in China and their alignment with renewable energy supply and demand. The study also explored core processes and technological challenges impacting UHS efficiency, including hydrogen loss mechanisms, multiphase flow behavior and reservoir integrity. Shahriar et al. [40] provided a comprehensive review of the crucial role of UHS in carbon neutrality and the hydrogen economy, examining storage losses, economic feasibility and infrastructure development. They emphasized the need for enhanced support in geomechanics, geochemistry and policy to drive technological advancement. Kumari et al. [41] explored the prospects and challenges of UHS in Australia and globally, focusing on reservoir characteristics such as salt cavern, hydrogen flow and reaction mechanisms, storage capacity and leakage risks, providing experimental and demonstration project support for future technological developments.

Cluster #1 emphasizes the importance of interdisciplinary approaches in salt cavern hydrogen storage research, particularly the application of machine learning in parameter modeling and system prediction, which helps improve the accuracy and efficiency of studies. This direction has driven the transition of research from traditional geological and engineering analyses to intelligent and automated approaches, providing technological support for refined management in complex hydrogen storage scenarios. Du et al. [42] explored the potential and challenges of UHS in China, covering three storage methods: salt

caverns, depleted oil and gas reservoirs, and aquifers. The study highlighted the potential of machine learning in optimization modeling and proposed directions to address scientific challenges, offering policy recommendations to achieve carbon neutrality goals.

Cluster #2 focuses on issues related to the geological characteristics of salt rock in China, particularly its layered structure and multi-layered features. Related research provides key scientific support for the design and engineering application of salt cavern hydrogen storage in China, promoting localized technological practices. Méndez et al. [43] investigated the impact of shotcrete lining on the stability of layered salt cavern hydrogen storage. The results indicated that shotcrete lining significantly improves the structural performance and durability of salt cavern, effectively reducing vertical displacement, axial strain and volumetric deformation at the top of the cavern, thus enhancing overall structural stability. This technology performs particularly well in wide cavern and deep high-temperature environments, but the study also emphasized the need for optimization between lining thickness, storage capacity and cost to achieve a balanced solution.

Cluster #3 focuses on issues related to hydrogen transportation, including forms of hydrogen transport (liquid hydrogen, ammonia, etc.), technological optimization and site selection. Ma et al. [44] reviewed the current status and challenges of large-scale storage and transportation of green hydrogen, covering methods such as compressed hydrogen storage, liquid hydrogen storage, pipeline transportation and ammonia as a hydrogen carrier. The study highlighted that technological advancements and economies of scale will lower costs, but challenges remain in optimizing storage methods, transportation models and efficiency. It also emphasized the need for research on salt cavern hydrogen storage, ammonia decomposition processes, and infrastructure transformation to provide direction for the sustainable hydrogen energy industry.

Cluster #6 explores the impact of permeability changes on hydrogen leakage risks from a microscopic perspective, emphasizing the central role of permeability in hydrogen storage safety assessments. Jadhawar et al. [45] evaluated the UHS performance of deep saline aquifers in the North Sea through 3D numerical simulations. The study found that improved permeability uniformity increases recovery efficiency, while relative permeability hysteresis effects lead to a reduction in hydrogen recovery. The individual effects of hydrogen dissolution and diffusion were found to be minor, but their combined influence with hysteresis effects was significant, highlighting the importance of a comprehensive analytical approach.

Cluster #7 is an emerging research theme in recent years, focusing on the potential threat of microbial activity to hydrogen loss and storage safety. This direction reveals the complexity of microbial–geological interactions during hydrogen storage, emphasizing the impact of microbial activity on hydrogen leakage and storage stability, providing a new research perspective for hydrogen storage safety management. Eberé et al. [46] evaluated the hydrogen storage potential of the Red River Group abandoned oil and gas reservoirs in North Dakota, finding that the reservoir has good porosity and permeability, with no significant geochemical changes or environmental impacts, making it suitable for long-term hydrogen storage. However, they suggest that future research should focus on microbial effects, buffer gas mixing, and caprock integrity to ensure safety and stability.

In summary, the keyword timeline chart illustrates the diversified research directions in the field of salt cavern hydrogen storage. From multi-energy collaboration, intelligent optimization, and geological characteristic studies to micro-mechanism analysis, the research comprehensively covers the key scientific and technical issues of salt cavern hydrogen storage, providing significant support for the large-scale application and sustainable development of this technology.

3. Discussion

With the growing global demand for clean energy, salt cavern hydrogen storage has gradually emerged as a key technology to meet large-scale energy storage needs owing to its excellent sealing performance, large storage capacity, and low cost. However, China's salt cavern hydrogen storage technology is relatively new and lags behind that of Europe and North America. The salt caverns in China are primarily composed of terrestrial, layered salt rock, characterized by low salt levels, numerous interlayers and high insoluble content. These unique geological conditions make it difficult to directly apply the mature salt dome-based hydrogen storage technologies from other countries.

In terms of the number of domestic research publications and collaboration networks in the field of salt cavern hydrogen storage, China has made significant progress in recent years. Over the past five years, the number of related publications in China has increased from 3 in 2020 to 18 in 2024, reflecting sustained research investment and rapid technological innovation. Core research institutions in China, such as the Chinese Academy of Sciences and Chongqing University, have formed a tight collaboration network in this field while also actively engaging in international cooperation, establishing close ties with technologically advanced countries such as the United States, Germany and Australia. This not only drives the development of hydrogen storage technologies under complex geological conditions but also lays a solid foundation for breakthroughs and large-scale applications of salt cavern hydrogen storage technology in China.

From a global perspective, research on salt cavern hydrogen storage technology has focused primarily on three areas: multi-energy synergy in UHS, system optimization design, and salt rock characteristics. Global research highlights the role of salt cavern hydrogen storage as a crucial component in multi-energy integration, enhancing the overall efficiency of energy systems by combining it with natural gas and carbon dioxide sequestration technologies. In terms of system optimization, studies focus on the integration of salt cavern hydrogen storage with renewable energy, evaluating its economic feasibility and operational stability for seasonal energy storage. Meanwhile, research on the physical and mechanical properties of salt rock provides fundamental support for hydrogen storage engineering design under complex geological conditions, particularly in terms of permeability control, hydrogen diffusion and the impact of microbial activity on storage stability. Overall, global research trends reflect a comprehensive development from basic theory to engineering practice, providing important scientific guidance for the large-scale and sustainable application of salt cavern hydrogen storage technology.

In order to better understand the similarities and differences in the development of salt cavern hydrogen storage technology between China and the rest of the world, as well as the driving factors behind these developments, the following analysis combines data to examine the characteristics, challenges, and potential solutions for China's salt cavern hydrogen storage technology. Figure 8 presents the co-occurrence network of keywords in China's salt cavern hydrogen storage field over the past five years, as indexed by WOSCC.

From Figure 8, it is evident that the high-frequency keywords in China's salt cavern hydrogen storage field primarily include salt cavern, hydrogen storage, energy storage, natural gas, rock salt, model, feasibility analysis, renewable energy, simulation, and permeability characteristics, which are categorized into six main research clusters. Research hotspots encompass system optimization and technical evaluation, multi-energy synergy, salt rock characteristics, engineering design, safety and permeability analysis, hydrogen storage fluid dynamics, and operational parameter optimization. These trends reflect that China's salt cavern hydrogen storage technology is gradually developing in both depth and breadth, providing clear guidance for future technological breakthroughs.

using VOSviewer and CiteSpace scientific knowledge mapping software, the development, current status, and challenges of domestic and international salt cavern hydrogen storage technologies are summarized. The main conclusions are as follows:

(1) In recent years, China has made substantial progress in salt cavern hydrogen storage technology. The number of publications increased from 3 papers in 2020 to 18 in 2024, covering various areas such as system optimization, multi-energy coordination and salt rock characteristics. Domestic research institutions, such as the Chinese Academy of Sciences and Chongqing University, have formed close collaboration networks and have partnered with leading countries like the United States, Germany, and Australia. This cooperation has further driven the continuous development of theoretical research and technological innovation.

(2) China's salt cavern hydrogen storage faces unique challenges in adapting to the complex geological conditions of layered salt rock, including multiple salt layers, high content of insoluble materials, and other issues that impose higher requirements on cavern stability and sealing. Additionally, problems such as thermodynamic coupling effects under high-frequency injection and extraction conditions, permeability control, and microbial activity have not yet been systematically addressed.

(3) The global research hotspots in salt cavern hydrogen storage primarily focus on the multifunctional collaborative applications of UHS, integration with renewable energy systems, economic feasibility, and commercialization. In contrast, research in China places more emphasis on foundational theories and simulations/optimizations in complex geological conditions. With the accumulation of technological practices and deeper international cooperation, China has significant room for improvement in research on microbial activity, engineering experience, and the introduction of intelligent technologies.

Looking forward, China should focus on its localized geological conditions, strengthen research on the sealing and permeability control of layered salt rock, and further optimize cavern design and operational parameters. At the same time, by learning from successful international cases, China should explore multi-energy coordination and commercialization pathways, gradually transforming theoretical research into practical engineering applications. With technological innovation, international collaboration and policy support, China's salt cavern hydrogen storage technology is expected to achieve rapid breakthroughs, providing strong support for the "dual carbon" goals and global energy transition.

Author Contributions: J.H.: Conceptualization, Data Curation, Methodology, Visualization, Writing—Original Draft, Writing—Review and Editing; X.G.: Funding Acquisition, Software, Investigation, Supervision; H.M.: Funding Acquisition, Project Administration, Supervision; X.S.: Funding Acquisition, Resources, Validation, Writing—Review and Editing; Y.L.: Formal Analysis, Validation. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge the financial support provided by the Excellent Young Scientists Fund Program of the National Natural Science Foundation of China (No. 52122403); the Young Scientists Fund of the National Natural Science Foundation of China (No. 52404060); and the Jiangxi Provincial Major Science and Technology Research and Development Program of China (No. 2023ACG01004).

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. United Nations. Global Issues. Our Population Growth. 2022. Available online: <https://www.un.org/en/global-issues/population> (accessed on 17 December 2024).

2. Minougou, J.D.; Gholami, R.; Andersen, P. Underground hydrogen storage in cavern: Challenges of impure salt structures. *Earth-Sci. Rev.* **2023**, *247*, 104599. [CrossRef]
3. Uliasz-Misiak, B.; Lewandowska-Śmierzchalska, J.; Matuła, R.; Tarkowski, R. Prospects for the Implementation of Underground Hydrogen Storage in the EU. *Energies* **2022**, *15*, 9535. [CrossRef]
4. National Development and Reform Commission of the People's Republic of China. Efforts to Achieve the Carbon. Peak and Carbon. Neutrality Goals. 2021. Available online: https://www.ndrc.gov.cn/wsdwhfz/202111/t20211111_1303691.html (accessed on 17 December 2024).
5. Xu, C.; Liu, J. Hydrogen Energy Storage in China's New-Type Power System: Application Value, Challenges and Prospects. *Strateg. Study Chin. Acad. Eng.* **2022**, *24*, 89–99. [CrossRef]
6. National Development and Reform Commission, National Energy Administration. Medium- and Long-Term Plan for the Development of the Hydrogen Energy Industry (2021–2035). 2022. Available online: https://zfxgk.nea.gov.cn/2022-03/23/c_1310525630.htm (accessed on 18 December 2024).
7. People's Republic of China, State Council. Energy Law of the People's Republic of China. 2024. Available online: https://www.gov.cn/yaowen/liebiao/202411/content_6985761.htm (accessed on 18 December 2024).
8. Li, H.; Cao, X.; Liu, Y.; Shao, Y.; Nan, Z.; Teng, L.; Peng, W.; Bian, J. Safety of hydrogen storage and transportation: An overview on mechanisms, techniques, and challenges. *Energy Rep.* **2022**, *8*, 6258–6269. [CrossRef]
9. Kamran, M.; Turzyński, M. Exploring hydrogen energy systems: A comprehensive review of technologies, applications, prevailing trends, and associated challenges. *J. Energy Storage* **2024**, *96*, 112601. [CrossRef]
10. Yang, C.; Wang, G.; Shi, X.; Zhu, S.; Zheng, Z.; Liu, W.; Fan, J.Y. Demands and challenges of large-scale salt cavern hydrogen storage in China. *Rock Soil Mech.* **2024**, *45*, 1–19.
11. Yan, H.; Zhang, W.; Kang, J.; Yuan, T. The Necessity and Feasibility of Hydrogen Storage for Large-Scale, Long-Term Energy Storage in the New Power System in China. *Energies* **2023**, *16*, 4837. [CrossRef]
12. Andersson, J.; Grönkvist, S. Large-scale storage of hydrogen. *Int. J. Hydrogen Energy* **2019**, *44*, 11901–11919. [CrossRef]
13. Zivar, D.; Kumar, S.; Foroozesh, J. UHS: A comprehensive review. *Int. J. Hydrogen Energy* **2021**, *46*, 23436–23462. [CrossRef]
14. Caglayan, D.G.; Weber, N.; Heinrichs, H.U.; Linßen, J.; Robinius, M.; Kukla, P.A.; Stolten, D. Technical potential of salt cavern for hydrogen storage in Europe. *Int. J. Hydrogen Energy* **2020**, *45*, 6793–6805. [CrossRef]
15. Ho, A.; Mohammadi, K.; Memmott, M.; Hedengren, J.; Powell, K.M. Dynamic simulation of a novel nuclear hybrid energy system with large-scale hydrogen storage in an underground salt cavern. *Int. J. Hydrogen Energy* **2021**, *46*, 31143–31157. [CrossRef]
16. China Energy News Network. Asia's First Large-Scale Deep Salt Cavern Hydrogen Storage Project Begins Construction. 2024. Available online: https://www.cpn.com.cn/news/hy/202411/t20241118_1751906.html (accessed on 18 December 2024).
17. Ge, X.; Huang, J.; Zhou, K.; Su, K.; Wang, W.; Li, Y.; Shi, X. Research of interlayer dip angle effect on stability of salt cavern energy and carbon storages in bedded salt rock. *Geoenergy Sci. Eng.* **2024**, *243*, 213291. [CrossRef]
18. Liu, W.; Li, Q.; Yang, C.; Shi, X.; Wan, J.; Jurado, M.J.; Li, Y.; Jiang, D.; Chen, J.; Qiao, W.; et al. The role of underground salt cavern for large-scale energy storage: A review and prospects. *Energy Storage Mater.* **2023**, *63*, 103045. [CrossRef]
19. Qiu, Y.; Zhou, S.; Wang, J.; Chou, J.; Fang, Y.; Pan, G.; Gu, W. Feasibility analysis of utilising underground hydrogen storage facilities in integrated energy system: Case studies in China. *Appl. Energy* **2020**, *269*, 115140. [CrossRef]
20. Małachowska, A.; Łukasik, N.; Mioduska, J.; Gębicki, J. Hydrogen storage in geological formations—The potential of salt cavern. *Energies* **2022**, *15*, 5038. [CrossRef]
21. Li, J. *Principles and Applications of Scientific Knowledge Graphs: A Beginner's Guide to VOSviewer and CitNetExplorer*; Higher Education Press: Beijing, China, 2018.
22. Li, J.; Goerlandt, F.; Reniers, G. An overview of scientometric mapping for the safety science community: Methods, tools, and framework. *Saf. Sci.* **2021**, *134*, 105093. [CrossRef]
23. Hibbard, L.; Gilfillan, S.M. Constraining the hydrogen storage capacity of natural gas storage sites in the United States. *Int. J. Hydrogen Energy* **2024**, *68*, 74–84. [CrossRef]
24. Tayeb, F.; Rouabhi, A.; AbuAisha, M.; Valtz, A. Kinetics of CO₂ dissolution for underground applications. *Geoenergy Sci. Eng.* **2023**, *230*, 212061. [CrossRef]
25. Tarkowski, R.; Uliasz-Misiak, B. Use of underground space for the storage of selected gases (CH₄, H₂, and CO₂)—Possible conflicts of interest. *Gospod. Surowcami Miner. Miner. Resour. Manag.* **2023**, *37*, 141–160. [CrossRef]
26. Wallace, R.L.; Cai, Z.; Zhang, H.; Guo, C. Numerical investigations into the comparison of hydrogen and gas mixtures storage within salt cavern. *Energy* **2024**, *311*, 133369. [CrossRef]
27. Alms, K.; Ahrens, B.; Graf, M.; Nehler, M. Linking geological and infrastructural requirements for large-scale underground hydrogen storage in Germany. *Front. Energy Res.* **2023**, *11*, 1172003. [CrossRef]
28. Takach, M.; Sarajlić, M.; Peters, D.; Kroener, M.; Schuldt, F.; von Maydell, K. Review of hydrogen production techniques from water using renewable energy sources and its storage in salt cavern. *Energies* **2022**, *15*, 1415. [CrossRef]

29. Kuterbekov, K.A.; Kabyshev, A.; Bekmyrza, K.; Kubenova, M.; Kabdrakhimova, G.; Ayalew, A.T. Innovative approaches to scaling up hydrogen production and storage for renewable energy integration. *Int. J. Low-Carbon Technol.* **2024**, *19*, 2234–2248. [\[CrossRef\]](#)
30. Epelle, E.I.; Obande, W.; Udourioh, G.A.; Afolabi, I.C.; Desongu, K.S.; Orivri, U.; Gunes, B.; Okolie, J.A. Perspectives and prospects of underground hydrogen storage and natural hydrogen. *Sustain. Energy Fuels* **2022**, *6*, 3324–3343. [\[CrossRef\]](#)
31. Liu, W.; Dong, Y.; Zhang, Z.; Li, L.; Jiang, D.; Fan, J.; Chen, J.; Zhang, X.; Wan, J.; Li, Z. Optimization of operating pressure of hydrogen storage salt cavern in bedded salt rock with multi-interlayers. *Int. J. Hydrogen Energy* **2024**, *58*, 974–986. [\[CrossRef\]](#)
32. Aftab, A.; Hassanpouryouzband, A.; Xie, Q.; Machuca, L.L.; Sarmadivaleh, M. Toward a fundamental understanding of geological hydrogen storage. *Ind. Eng. Chem. Res.* **2022**, *61*, 3233–3253. [\[CrossRef\]](#)
33. Li, D.-P.; Liu, W.; Fu, P.; Li, L.; Ban, F.-S.; Li, Q.-H.; Fan, J.-Y.; Jiang, D.-Y.; Zhang, Z.-X. Stability evaluation of salt cavern hydrogen storage and optimization of operating parameters under high frequency injection production. *Gas Sci. Eng.* **2023**, *119*, 205119. [\[CrossRef\]](#)
34. Grgic, D.; Al Sahyouni, F.; Golfier, F.; Moumni, M.; Schoumacker, L. Evolution of gas permeability of rock salt under different loading conditions and implications on the underground hydrogen storage in salt cavern. *Rock Mech. Rock Eng.* **2022**, *55*, 691–714. [\[CrossRef\]](#)
35. Falcon-Suarez, I.H.; Dale, M.; Marin-Moreno, H. Experimental study of geophysical and transport properties of salt rocks in the context of underground energy storage. *Geophys. Prospect.* **2024**, *72*, 2032–2048. [\[CrossRef\]](#)
36. Navaid, H.B.; Emadi, H.; Watson, M. A comprehensive literature review on the challenges associated with underground hydrogen storage. *Int. J. Hydrogen Energy* **2023**, *48*, 10603–10635. [\[CrossRef\]](#)
37. Li, J.; Chen, C. *CiteSpace: Text Mining and Visualization in Scientific Literature*; Capital University of Economics and Business Press: Beijing, China, 2022.
38. Chen, C. CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *J. Am. Soc. Inf. Sci. Technol.* **2006**, *57*, 359–377. [\[CrossRef\]](#)
39. Chen, Y.; Jin, X.; Zeng, L.; Zhong, Z.; Mehana, M.; Xiao, W.; Pu, W.; Regenauer-Lieb, K.; Xie, Q. Role of large-scale underground hydrogen storage and its pathways to achieve net-zero in China. *J. Energy Storage* **2023**, *72*, 108448. [\[CrossRef\]](#)
40. Shahriar, M.F.; Khanal, A.; Khan, M.I.; Pandey, R. Current status of underground hydrogen storage: Perspective from storage loss, infrastructure, economic aspects and hydrogen economy targets. *J. Energy Storage* **2024**, *97*, 112773. [\[CrossRef\]](#)
41. Kumari, W.; Ranjith, P. An overview of underground hydrogen storage with prospects and challenges for the Australian context. *Geoenergy Sci. Eng.* **2023**, *231*, 212354.
42. Du, Z.; Dai, Z.; Yang, Z.; Zhan, C.; Chen, W.; Cao, M.; Thanh, H.V.; Soltanian, M.R. Exploring hydrogen geologic storage in China for future energy: Opportunities and challenges. *Renew. Sustain. Energy Rev.* **2024**, *196*, 114366. [\[CrossRef\]](#)
43. Méndez-Vázquez, S.; Soage, A.; Navarrina, F.; París, J.; Colominas, I.; Cueto-Felgueroso, L.; Juanes, R. Effect of a gunite lining on the stability of salt cavern in bedded formations for hydrogen storage. *Int. J. Hydrogen Energy* **2024**, *90*, 298–316. [\[CrossRef\]](#)
44. Ma, N.; Zhao, W.; Wang, W.; Li, X.; Zhou, H. Large scale of green hydrogen storage: Opportunities and challenges. *Int. J. Hydrogen Energy* **2024**, *50*, 379–396. [\[CrossRef\]](#)
45. Jadhawar, P.; Saeed, M. Mechanistic evaluation of the reservoir engineering performance for the underground hydrogen storage in a deep North Sea aquifer. *Int. J. Hydrogen Energy* **2024**, *50*, 558–574. [\[CrossRef\]](#)
46. Ebere, F.O.; Jabbari, H. Unlocking UHS potential: Geochemical characterization of North Dakota's geological formation. *Int. J. Hydrogen Energy* **2024**, *93*, 250–272. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.