energies

Review

Underground Hydrogen Storage: Transforming Subsurface Science into Sustainable Energy Solutions

Kwamena Opoku Duartey [1,2,*], William Ampomah [1,2,*], Hamid Rahnema [2] and Mohamed Mehana [3]

1 Petroleum Recovery and Research Center, New Mexico Tech, Socorro, NM 87801, USA
2 Petroleum and Natural Gas Department, New Mexico Tech, Socorro, NM 87801, USA; hamid.rahnema@nmt.edu
3 Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, NM 87544, USA; mzm@lanl.gov
* Correspondence: kwamena.opokuduartey@student.nmt.edu (K.O.D.); william.ampomah@nmt.edu (W.A.)

Abstract: As the global economy moves toward net-zero carbon emissions, large-scale energy storage becomes essential to tackle the seasonal nature of renewable sources. Underground hydrogen storage (UHS) offers a feasible solution by allowing surplus renewable energy to be transformed into hydrogen and stored in deep geological formations such as aquifers, salt caverns, or depleted reservoirs, making it available for use on demand. This study thoroughly evaluates UHS concepts, procedures, and challenges. This paper analyzes the most recent breakthroughs in UHS technology and identifies special conditions needed for its successful application, including site selection guidelines, technical and geological factors, and the significance of storage characteristics. The integrity of wells and caprock, which is important for safe and efficient storage, can be affected by the operating dynamics of the hydrogen cycle, notably the fluctuations in pressure and stress within storage formations. To evaluate its potential for broader adoption, we also examined economic elements such as cost-effectiveness and the technical practicality of large-scale storage. We also reviewed current UHS efforts and identified key knowledge gaps, primarily in the areas of hydrogen–rock interactions, geochemistry, gas migration control, microbial activities, and geomechanical stability. Resolving these technological challenges, regulatory frameworks, and environmental sustainability are essential to UHS's long-term and extensive integration into the energy industry. This article provides a roadmap for UHS research and development, emphasizing the need for further research to fully realize the technology's promise as a pillar of the hydrogen economy.

Keywords: underground hydrogen storage; geochemical interactions; hydrodynamics; cushion gas; microbial effects

Academic Editors: Samuel Simon Araya and Vincenzo Liso

Received: 31 December 2024
Revised: 24 January 2025
Accepted: 27 January 2025
Published: 6 February 2025

Citation: Opoku Duartey, K.; Ampomah, W.; Rahnema, H.; Mehana, M. Underground Hydrogen Storage: Transforming Subsurface Science into Sustainable Energy Solutions. *Energies* **2025**, *18*, 748. https://doi.org/10.3390/en18030748

1. Background and Significance of UHS

By 2050, it is anticipated that there will be 10 billion people on Earth and there will be an increasing need for energy to meet this growth and demand [1]. To be able to address this need, many countries are turning to renewable energy sources as a supplement to fossil fuels. The limited resource of fossil fuels necessitates the usage of alternative energy sources as the need for energy rises [2]. Consuming fossil fuels without extreme environmental controls substantially impacts the environment, including greenhouse gas emissions that lead to global warming [3]. Scientists have emphasized that if global warming continues unchecked, the consequences will be severe. However, immediate action is still needed to mitigate global warming such as reducing greenhouse gas emissions by integrating more sustainable energy into our energy mix, advancing carbon capture and storage (CCS), and increasing climate resilience and adaptation. The *World Energy Outlook 2024* reports that renewable energy is outpacing electricity demand growth, reducing fossil fuel dependency. In 2023, renewables supplied 30% of the global electricity, while fossil fuels dropped to 60%, which is their lowest share in 50 years.

In 2020, carbon emissions from energy use dropped by over 6%, marking the most significant decline since 1945, which was driven by a sharp reduction in global primary energy demand due to the impacts of the global COVID-19 pandemic on energy markets. Thus, the decline in the energy demand primarily impacted fossil fuels, while renewables, especially hydroelectricity, wind, and solar, continued to grow because of their competitive costs and supportive policies. This reduction aligns with the increasing adoption of renewables such as wind, solar, and hydroelectric power, which continued to grow despite the overall energy downturn [3]. These energy sources depend on seasonal changes in sunlight, wind strength, and other geographical factors. The interplay and changing yearly energy demands can result in either excess or shortages of renewable energy. Because of the unpredictability of these renewable sources, hydrogen offers a reliable alternative that is not dependent on seasons. It can be stored and used when demand increases. Hydrogen can be derived from both renewable and non-renewable sources. It has the highest energy content and is the most common and lightest element [4]. Hydrogen can be seen as a key replacement for fossil fuels because it can be burned, stored, and used similarly. This makes hydrogen an attractive alternative for decarbonizing high-demand industries such as shipping, aviation, and steel and iron production [5–7]. The smooth operation of large-scale hydrogen value chains requires adequate storage capacity and performance. Geological storage is considered the most effective method for large-scale, long-term storage. Hydrogen can be stored in underground geological formations such as aquifers, rock caverns, and depleted oil and gas reservoirs [8]. Subsurface hydrogen storage is less advanced than gas storage methods like CO_2 and CH_4. Large-scale underground hydrogen storage is crucial for managing seasonal energy supply and driving the hydrogen economy. Hydrogen storage plays an important role in enhancing electricity system stability, integrating renewable energy sources, and advancing decarbonization efforts. It provides long-term energy storage, enhances energy security, and powers industries and transportation [9]. Underground natural gas (UGS) has several similarities to underground hydrogen storage (UHS). The knowledge gained in UGS can often be applied to UHS projects such as site selections, storage methods, monitoring, and managing injection and withdrawal cycles. The key fundamental difference is that hydrogen has a higher chemical reactivity compared to natural gas, meaning that hydrogen can participate in biological, microbial, and chemical activities [10]. In addition, unique hydrogen properties such as mobility and low viscosity result in fingering, gravity segregation, and overriding [10].

Hydrogen may become a major energy vector by 2050, supplementing or replacing coal and natural gas by 2050 [11]. It is predicted to be widely employed in aviation, shipping, transportation, steelmaking, and chemicals. H_2 plays a crucial role in efforts to establish a carbon-neutral economy, thereby supporting goals outlined in the Paris Climate Agreement and the European Green Deal.

This paper reviews the potential of underground hydrogen storage to meet the growing global energy demand by 2050. It highlights technological advancements, environmental benefits, and economic feasibility, emphasizing its role in reducing greenhouse gas emissions. Addressing gaps in existing research, this study covers storage capacity, efficiency, safety, and sustainability, along with integration into renewable energy systems. It also evaluates policy frameworks and real-world applications, offering insights for enhancing energy security and promoting the adoption of hydrogen storage.

2. Sources of Hydrogen

Hydrogen production-related CO_2 emissions vary depending on the energy source, including wind, solar, biomass, natural gas, and nuclear. Electrolysis, which employs water to produce H_2, has evolved greatly to produce low-emission options. Most of the hydrogen produced today comes from natural gas (76%) and coal (23%), while some sources are produced via electrolysis [11]. The EU used 7.94 million metric tons of hydrogen in 2024, largely in refineries (57%) and the chemical industry, where it is used to manufacture products like ammonia (25%) and methanol (12%), which account for 8% of global production. However, most EU-produced hydrogen is still "gray", meaning it comes from fossil fuels rather than renewable resources [11]. The various processes that produce hydrogen are represented by the colors blue, green, black, brown, turquoise, yellow, pink, gray, and white in Figure 1. These colors also symbolize how each process affects the environment. The three most abundant forms of hydrogen are green, gray, and blue [11].

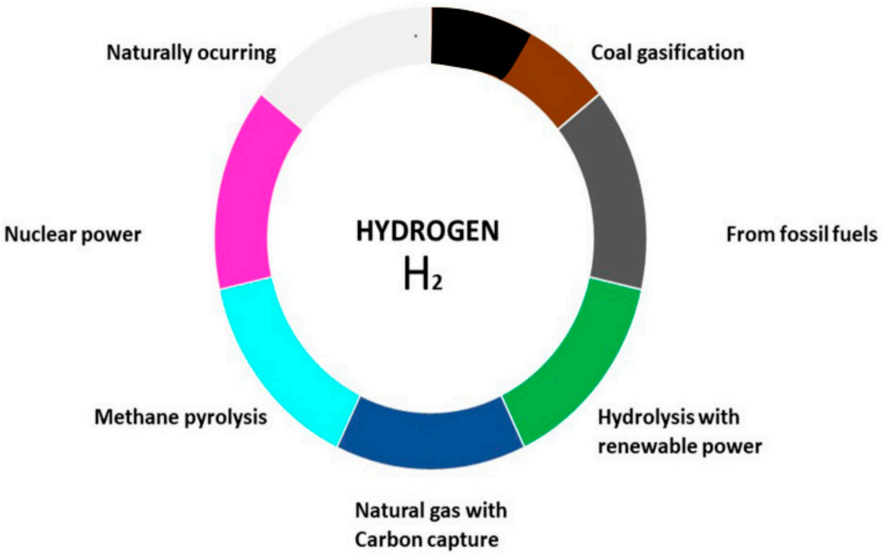

Figure 1. The various processes that produce hydrogen. Modified from [12].

Hydrogen derived from fossil fuels is known as gray hydrogen, which is produced through the steam methane reforming process and releases CO_2 emissions. At about USD 1 per kilogram, this method remains the most cost-effective way to produce hydrogen, accounting for around 6% of the world's natural gas. Carbon capture and storage (CCS) can help mitigate emissions from gray hydrogen, but as clean energy alternatives expand, green hydrogen is expected to gradually grow [12]. Endothermic steam reformation uses steam that is between 700 °C and 1000 °C.

$$2CH_4 + 2H_2O \rightleftharpoons 2CO + 3H_2 \ \Delta H = +206 \text{ kJ/mol} \tag{1}$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \ \Delta H = -41 \text{ kJ/mol Water-gas shift reaction exothermic} \tag{2}$$

The cost of producing gray hydrogen is influenced by several technical and financial factors, with capital expenditures and gas costs being the most significant. Between 45% and 75% of production costs are attributed to gas expenses. Additionally, the production of hydrogen from this process generates 9–12 tons of CO_2 per unit of hydrogen produced [13]. The production of blue hydrogen involves steam methane reforming, with carbon capture and storage (CCS) technologies used to capture the CO_2 emissions produced during its generation [14]. The most common technique for generating hydrogen today is this fossil fuel-based process. In 2024, the price of producing hydrogen using fossil fuels ranged from

USD 0.98 to USD 2.93 per kilogram, according to the IEA, which is about three times cheaper than the peak pricing for hydrogen generated from renewable electricity [12]. Although this price disparity is predicted to shrink by 2050, blue hydrogen will likely remain the more economical option. Future costs will depend on factors such as technological advancements, production scale, availability of CO_2 storage, and price of natural gas. However, blue hydrogen synthesis is energy-intensive; only 70–75% of the initial natural gas heat is retained in the final hydrogen product. Additionally, in order to reach carbon neutrality, adding carbon capture and storage (CCS) technology raises production costs by roughly USD 0.5 per kilogram, with overall costs varying between USD 1.5 and USD 2.5 per kilogram, depending on natural gas prices [12].

In contrast, green hydrogen is generated through zero-emission methods like water electrolysis powered by renewable energy sources like solar, wind, and biomass gasification [15]. Hydrogen production from biomass, particularly through biological processes, is a promising avenue for sustainable energy generation. Dark fermentation biohydrogen production, classified as "green hydrogen", utilizes renewable feedstocks such as organic waste, biomass, or wastewater to produce hydrogen through anaerobic microbial fermentation [16]. This process offers several advantages, including low environmental impact, carbon-neutral potential, and the ability to integrate waste management with energy production. However, challenges such as low yields and production rates persist, necessitating further research and development. Green hydrogen is costly so it currently makes up only a portion of the hydrogen mix. According to a study conducted in 2020, called "Path to Hydrogen Competitiveness", the cost of green hydrogen is about USD 6/kg, which makes it costlier than blue and gray hydrogen [12]. Aiming to promote hydrogen to facilitate the clean energy transition, the worldwide CEO-led Hydrogen Council, composed of top companies, is pushing for USD 2/kg to be the tipping price point for green hydrogen to become a desirable option for use in a variety of industries [17]. Influenced by global goals, trends, and sector-specific actions, Price Waterhouse Coopers (PwC) forecasts that green hydrogen demand will rise modestly until 2030 and reach 150–500 million tons annually by 2050.

Black hydrogen is produced by gasifying coal to create syngas, a mixture of carbon dioxide, hydrogen, carbon dioxide, and methane. The composition of syngas can vary based on the feedstock and gasification method used. This process involves heating coal at high temperatures with steam and oxygen. Brown hydrogen, on the other hand, is produced directly from coal through a more basic method of extraction, typically without the additional step of gasification. In both processes, the hydrogen output can be enhanced by further treatment of the syngas. However, black hydrogen is typically associated with a more complex gasification process, while brown hydrogen comes from simpler, less processed coal [17].

$$C + O_2 + H_2O \rightleftharpoons 3CO + H_2 \tag{3}$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \ \Delta H = -41\ \text{kJ/mol water-gas shift reaction} \tag{4}$$

The cost of producing brown hydrogen is between USD 1.20 and USD 2.20 per kilogram. However, each year, it emits a considerable amount of CO_2, approximately 830 million tonnes, which is not environmentally desirable. The market for brown hydrogen is projected to reach USD 48.9 billion by 2030, driven by its economic benefits. However, over time, environmental concerns regarding emissions may reduce its appeal.

Pink hydrogen, also known as purple or red hydrogen, is produced by using nuclear energy to electrolyze water. Initiatives in the United States and the United Kingdom are advancing the use of nuclear energy for hydrogen production, with costs currently between USD 2 and USD 6 per kilogram. In the next decade, the U.S. Department of Energy (DOE) aims to reduce the cost of clean hydrogen generated from hybrid nuclear systems, which use leftover heat and electricity, down to USD 1 per kilogram [12]. Nuclear hydrogen generation costs anywhere from USD 2 to USD 6 depending on the production process. For example, the Japan Atomic Energy Agency has successfully tested this technique on a small scale and intends to produce hydrogen for under USD 3 per kilogram using high-temperature reactors [18].

The turquoise hydrogen method uses a process of methane pyrolysis, thus splitting natural gas into solid carbon and hydrogen without emitting CO_2. When powered by renewable energy, turquoise hydrogen is carbon-neutral. Companies like Mitsubishi are investing in turquoise hydrogen as an appealing option that bridges traditional and renewable hydrogen production, leveraging existing gas infrastructure with minimal emissions. The process becomes carbon neutral if the energy required to produce heat for the breakdown of natural gas comes from renewable sources [19]. The process may be carbon-negative if the natural gas is derived from biogenic sources. The goal is to increase the appeal of turquoise hydrogen to consumers by lowering its price to conventionally produced (gray) hydrogen.

White hydrogen is a naturally occurring substance that occurs in rock formations and geological zones of the Earth's crust without the help of humans. A potentially carbon-neutral resource, it has been found in regions like Australia and Mali, though it has not been widely exploited so far [20]. Early modeling assessment by the U.S. Geological Survey (USGS) indicates that the United States has at least two key regions with promising geology for significant natural hydrogen accumulations: the Atlantic Coastal Plain and central areas such as the Great Plains and the Upper Midwest. Like natural gas production, hydrogen can become a clean, affordable energy source. There will probably be more exploration and extraction projects as the field develops. Hydrogen, produced from geologic sources deep underground, holds significant potential as the most cost-effective and competitive alternative to fossil fuels. While estimates of its global production vary, research suggests that hydrogen may be present in large quantities in the Earth's crust. Recently, large hydrogen reservoirs have been identified, driving new exploration efforts. This finding has generated a wave of rivalry among businesses seeking exploration rights, with 18 white hydrogen drilling licenses already issued or filed in South Australia. Despite these advancements, the white hydrogen market remains in the initial stages of development [12].

3. General Consideration of Underground Hydrogen Storage

The small molecular size, low density, and viscosity of hydrogen pose a major concern for storage. A good reservoir for a hydrogen storage system should have suitable permeability and porosity with a great caprock seal. Geological storage formation approaches vary in terms of depth deposits, lithology of the site storage, storage capacity, geological tightness, recent experience, availability of structures, and existing infrastructure. Geological, technical, environmental, and economic factors are critical in site selection [20]. Hydrogen exhibits low solubility in water and argillaceous rocks, with a correspondingly low diffusion coefficient. During storage cycles, 1% is lost due to operational procedures and 0.4% due to hydrogen dissolving in brine, causing undesired hydrodynamic behavior. The hydrodynamic behavior during cyclic processes shows unwanted behaviors such as viscous fingering, cushioning gas mixing, and lateral spreading [21]. These events have led to the development of numerically simulated strategies to mitigate the adverse subsurface hydrodynamic behavior of hydrogen. Key mitigation techniques employed are selective technology, increasing the number of storage cycles, optimizing the arrangement of extracted wells, and controlling the injection rate [22]. Hydrogen can also catalyze subsurface settings and induce bacterial activity, which may lead to several adverse effects, including hydrogen loss, compromised geological integrity, and reduced permeability. The impact of the subsurface hydrodynamic behavior of hydrogen is a universal concern for all underground hydrogen storage (UHS) methods, but it is particularly significant for depleted reservoirs and aquifers [21,22]. Fluid management in underground hydrogen storage must address challenges such as environmental concerns and rheological performance [23]. The distinct physical characteristics of hydrogen have major relevance in the effectiveness of underground hydrogen storage (UHS). Hydrogen is significantly less dense compared to methane and carbon dioxide, which have been extensively researched and stored underground for years. Hydrogen's lower viscosity and solubility enhance the efficiency in storage and retrieval cycles, preventing fluid coning problems and reducing losses in saline aquifers or depleted reservoirs, particularly in water, hydrogen, and salt systems [24]. Table 1 illustrates the differences in the physiochemical properties of H_2, CO_2, and CH_4 that are relevant for consideration during storage purposes.

Table 1. Physiochemical properties [20,24].

Properties	CO_2	CH_4	H_2
Molecular weight (u)	44.09	16.043	2.016
Critical temperatures (°C)	−31	−82.3	−239.95
Density (25 °C, 1 atm)/kg/m^3	1.98	0.657	0.082
Viscosity (25 °C, 1 atm)/Pa s	1.49×10^{-5}	1.1×10^{-5}	0.89×10^{-5}
Boiling point (°C)	−78.44	−165	−253
Critical pressure (atm)	72.79	45.79	12.8
Diffusion in pure water (25 °C, 1 atm)/m^2/s	1.60×10^{-3}	1.85×10^{-9}	5.13×10^{-9}
Flash point (°C)	-	−188	−253
Heating value (kJ/g)	-	50–55.5	120–142
Solubility in pure water (25 °C, 1 atm)/g/L	1.45×10^{-3}	22.7×10^{-3}	16×10^{-4}
Auto ignition temperature (°C)	-	540	585
Flammability (°C)	-	5–15	4–75

4. Key Drivers for Utility-Scale UHS

To overcome the problem of energy curtailment that emerges with renewable sources, utility-scale UHS is crucial. Because of fluctuating weather, shifting demand, sluggish transmission networks, fluctuating fuel prices, varying consumption patterns, and geographic constraints, extra energy frequently goes underutilized during peak output periods. To augment the total dependability and efficiency of renewable resources, UHS offers an effective solution for storing excess energy for later use. Effectively capturing and storing excess renewable energy such as hydrogen (H_2) can help mitigate seasonal fluctuations in renewable energy generation. When renewable energy production is low, utilizing this storage method minimizes and optimizes the use of clean energy resources [25–27]. Leveraging natural gas infrastructure for UHS can significantly boost H_2 storage capacity quickly and affordably, reducing additional investments and expediting utility-scale deployment, thereby facilitating a low-carbon energy future. Global interest in H_2 production projects and political actions for their widespread use has increased, with national and international projects aiming to increase H_2 production, as shown in Figure 2. There have been 1572 clean hydrogen projects announced globally as of May 2024. Since the last report, there has been a net rise of 154 projects. Approximately USD 680 billion will have been invested in hydrogen value chains, up from USD 570 billion in the past, with 1125 of these projects expected to reach commercial operation by 2030. Interestingly, giga-scale projects account for more than half of this investment, which totals more than USD 380 billion [28].

Figure 2. Global hydrogen projects and investment overview in 2024 [28].

The storage of large volumes of energy above the Earth appears unworkable due to pressure limitations and the need for specialized materials. Long-term use and extensive energy output make UHS more feasible. UHS technology improves the feasibility for extended duration and large-scale energy generation. Figure 3 data encompass gigawatt-hours to terawatt-hours over timeframes ranging from weeks to seasons in salt caverns and porous media such as saline aquifers and depleted reservoirs [26,29].

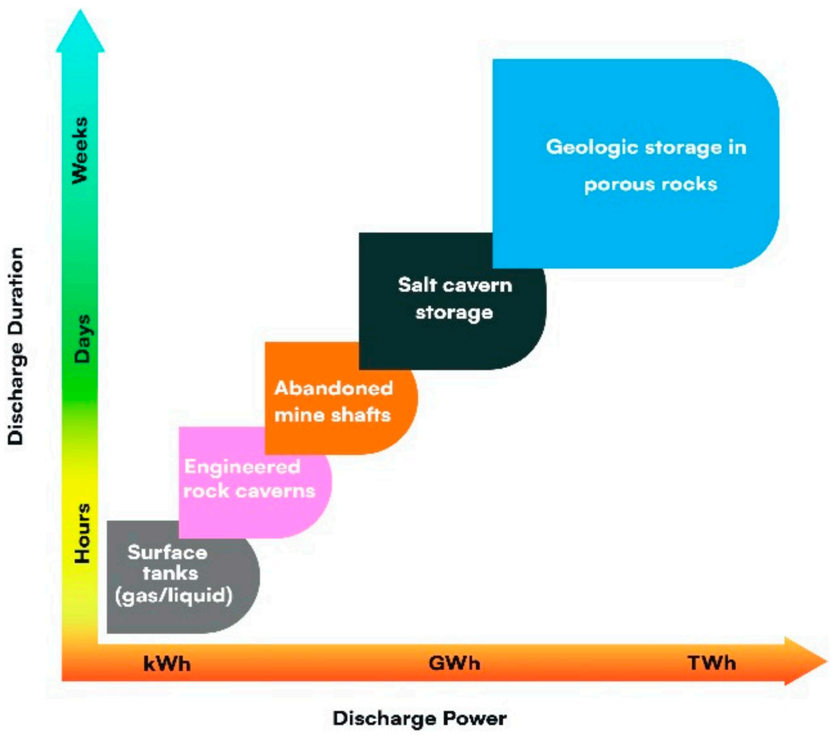

Figure 3. Hydrogen storage options with corresponding storage power and duration.

The global spread of subterranean hydrogen storage projects is being fueled by the switch to renewable energy sources, advancements in subsurface storage technologies, and increased investments in sustainable energy infrastructure. Table 2 gives an overview and summary of worldwide underground hydrogen storage (UHS) demonstration projects and feasibility studies conducted in many nations. Germany leads with the biggest number of projects, which are mostly focused on feasibility studies for porous formations. Other notable countries, such as the Netherlands and the United States, also show significant interest in cavern and porous storage planning. Operational projects remain restricted, illustrating the early-stage development of UHS technology worldwide.

Table 2. Global outlook of the development of underground hydrogen storage projects [30–32].

Location	Project Name	Storage Type	Storage Capacity	Status
USA	Moss Bluff	Salt cavern	120–123 GWh	Successful
	Clemens Dome	Salt cavern	81–92 GWh	Successful
	Advance Clean Energy Storage	Salt cavern	300 GWh	
	Spindle Top	Salt cavern	274 GWh	Successful
UK	Teesside	Salt cavern	25–27 GWh	Successful
	HySecure	Salt cavern	Over 1.2 GWh	Prospective
	ANGUS+	Depleted gas field	-	
	Midland Valley	Oil reservoir	-	
	Rough Gas Storage Facility	Depleted natural gas reservoir	-	
Germany	GET H2 Nukleus Gronau-Epe	Salt cavern	2.33 GWh	
	Bad Lauchstädt	Salt cavern	150 GWh	
	Kiel	Salt cavern	6.327 KWh	Successful
	Ketzin	Aquifer	4.33 TWh	Successful
	Caves & Waves	Salt cavern		
	Rhaetian, Schleswing Holstein	Gas reservoir		
Argentina	Hychico	Depleted gas field	10–30 MW	Prospective
Belgium	Loenhout Hydrogen	Aquifer	2–3 TWh	Prospective
Ireland	Green hydrogen@Kinsale	Depleted gas field	3 TWh	Prospective
Poland	Damasławek	Salt cavern	Unknown	
France	HyCAVMobil Rüdersdor	Salt cavern	167–200 MWh	Successful
	HyGreen Provence	Salt cavern	Unknown	
	Hypster	Salt cavern		
	HyGéo	Salt cavern	1.5 GWh	
	Westküste 100	Salt cavern	Unknown	
	H2Cast	Salt cavern	Unknown (scalable)	
	Jemgum Storage	Salt cavern	506.4 GWh	
	HPC Krummhörn	Salt cavern	1.8 GWh	
Italy	North Adriatic Hydrogen Valley	Depleted gas field	Unknown	
Sweden	HyBRIT	Lined rock cavern	300–360 MWh	Prospective
Portugal	Sines H2 Hub, Carriço	Salt cavern	Unknown	
Netherlands	HyStock	Salt cavern	806.4 MWh	
Slovakia	H2I	Depleted gas field	Unknown	
Spain	San Pedro belt	Saline aquifer	Unknown	
Turkey	Tuz Golu gas storage	Salt cavern		
Hungary	Aquamarine	Depleted gas field	Unknown	
Canada	Mount Simon Aquifer	Saline aquifer	Unknown	
	Salina A2&B	Salt cavern		

Table 2. *Cont.*

Location	Project Name	Storage Type	Storage Capacity	Status
Austria	Sun Storage 2030	Depleted gas field	4.2 GWh	
	Sun Storage FlexStore	Depleted gas field	Unknown	
	HyStorage Bierwang	Depleted gas field		
	Sun Conversion FlexStore	Depleted gas field	Unknown (Texting Only)	

The global hydrogen storage capacity is projected to grow significantly in the coming years with various estimates highlighting its potential. According to Statista, the hydrogen storage capacity is expected to reach 10 terawatt-hours (TWh) by 2035, with announced projects suggesting a capacity of 40 TWh [33]. This growth is crucial for supporting the transition to a carbon-free future, although these figures may still fall short of the anticipated needs. Recent advancements in underground hydrogen storage demonstrate significant progress in capacity, efficiency, and technological innovation. The HyStock project in the Netherlands has seen significant interest, with market demand exceeding the offered capacity during its open session in 2023. The project located in Zuidwending, Groningen, in the Netherlands is developing four salt caverns, each capable of storing 20 kilotonnes of hydrogen (216 GWh). The first cavern is expected to be operational by 2029 [34]. In France, the HyPSTER project successfully injected hydrogen into the EZ53 salt cavern at Etrez in October 2024, aiming to store 2 tons of hydrogen, and conducted injection and withdrawal cycles [35]. This demonstration sets the stage for industrial-scale hydrogen storage in Europe. Sandia National Laboratories' research in 2024 focused on storing hydrogen in depleted oil and gas reservoirs, contributing to the SHASTA project [36]. The findings will inform future large-scale field tests of underground hydrogen storage. Vallourec's innovative vertical Hydrogen Storage System, developed in 2024, can store up to 100 metric tons of hydrogen underground, occupying 30 times less surface area than above-ground alternatives [37]. The HyStorage Project in Germany achieved a 90% recovery rate of injected hydrogen in porous rock formations during its 2024 test phase with no significant impact on reservoir performance or material corrosion [38]. The Advance Clean Energy Storage Facility in Utah, USA, is designed to store 100 metric tonnes of green hydrogen daily in salt caverns [39], while the Krummhörn Hydrogen Storage Facility in Germany, opened in 2024, has a total storage volume of 500,000 norm cubic meters of green hydrogen. These projects demonstrate advancements in underground hydrogen storage technologies, including high recovery rates (e.g., HyStorage, 90%), scalability (e.g., HyStock's 216 GWh capacity), and successful integration with renewable energy systems. However, challenges such as cost reduction and further optimization remain key focus areas for future development.

UHS Global Initiatives and Cooperation for Low-Carbon Future

Underground hydrogen storage (UHS) is poised to play a crucial role in the global energy transition, offering a strategic solution for large-scale energy storage to support the shift towards renewable energy systems. The outlook for UHS is increasingly positive, with a significant potential impact on the future energy landscape. The U.S. Department of Energy (DOE) office of Fossil Energy and Carbon Management (FECM) has been leading efforts to investigate and promote UHS technology [40]. The DOE national laboratories are actively involved in UHS research. The Subsurface Hydrogen Assessment, Storage, and Technology (SHASTA) project, funded by the DOE, is a collaborative effort among these national laboratories to determine the viability, safety, and reliability of storing hydrogen underground. Europe is at the forefront of underground hydrogen storage (UHS) development, with several significant initiatives and projects underway: EUH2STARS, a European flagship project supported by the Clean Hydrogen Partnership, aims to demonstrate a competitive and qualified UHS system in depleted porous natural gas reservoirs by the end of the decade [41]. HyUnder is a project initiated in 2012 to establish a European Initiative supporting the deployment of hydrogen energy storage in underground caverns at a large scale [42]. The HyStorIES project, which ran from January 2021 to December 2022, focused on validating UHS solutions in depleted fields and aquifers across Europe. Hystories is a research project that concluded in June 2023, which concentrated on storing hydrogen in porous reservoirs like depleted fields and aquifers [43]. H2eart for Europe, which was formed in July 2024, is an alliance of European storage system operators that released a roadmap for UHS deployment [44]. These initiatives involve collaboration among various European countries, including Austria, Hungry, the Netherlands, Spain, Norway, and many others. The aim is to address technical challenges, develop regulatory frameworks, and accelerate the adoption of UHS technology as part of Europe's Transition to a low-carbon economy. To promote the widespread adoption of UHS technology, the following cooperation initiatives are proposed: Public–Private Partnerships: Governments and energy companies should collaborate to develop UHS infrastructure, sharing risks and investments. Research and Development Consortia: International research groups should be formed to address technical challenges, such as hydrogen behavior in the subsurface and reservoir selection criteria. Regulatory Frameworks: Governments should work together to establish clear standardized regulations for UHS operations, ensuring safety and environmental protection. Knowledge Sharing Platforms: Global forums should be created for sharing best practices, operational experiences, and technological advancements in UHS. Supply Chain Integration: Efforts should be made to coordinate between hydrogen producers, storage operators, and end-users to create an efficient hydrogen ecosystem. Infrastructure Planning: Comprehensive plans should be developed for hydrogen pipeline networks and storage facilities, involving both government agencies and private sector stakeholders. International Trade Agreements: Protocols for cross-border hydrogen trade should be established, considering the potential for some regions to become net importers or exporters. Technology Transfer Programs: The exchange of UHS technologies and expertise should be facilitated between developed and developing countries to accelerate global adoption. Education and Training Initiatives: Programs should be developed to train the workforce required for the growing hydrogen economy, including UHS specialists. By implementing these cooperation proposals, stakeholders can accelerate the development and deployment of UHS technology, supporting the global energy transition and shift towards a low-carbon future.

5. Subsurface Geological Formations for UHS

There are several types of UHS options currently under consideration: (a) aquifers, which are natural underground water reservoirs; (b) depleted hydrocarbon deposits, such as those in natural gas or oil reservoirs; (c) salt caverns, which are created by dissolving rock salt; and (d) subterranean mining areas, including abandoned salt or limestone mines along with rock caverns. Each option offers unique characteristics that influence the hydrogen storage efficiency and suitability as shown in Figure 4.

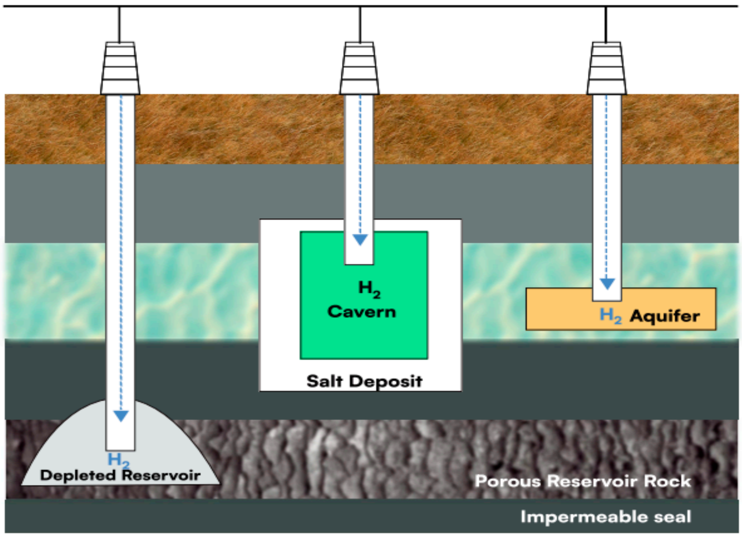

Figure 4. Hydrogen storage in porous reservoir rocks modified from [45].

5.1. Depleted Oil and Gas Reservoirs

Depleted oil and gas fields have suitable infrastructure and clearly defined geological formations, making them a good candidate for hydrogen storage. Formation storage capacity, storage depth, and caprock formation thickness are essential considerations when choosing a storage location [20]. Depleted gas offers advantages, particularly residual gas and well-characterized underlying structures. Hydrogen is preserved in geological formations by mostly reversible trapping mechanisms such as structural/stratigraphic, capillary trapping, and solubility/dissolution in fluids. A number of parameters must be satisfied for UHS in depleted reservoirs to operate reliably over the long term. A comprehensive assessment of a reservoir's structural integrity, economic feasibility, and safety is important. The demonstrated tightness of depleted hydrocarbon reservoirs, filled with gas confined for millions of years, is a major benefit of using them. Residual gases might persist in the reservoirs chosen for UHS, and they might serve as cushion gases and aid in pressure maintenance. A cushion gas volume of 50–60% is typically required [45,46]. Notwithstanding this economic advantage, hydrogen may mix with the reservoir's residual native gases. The extent of interactions between several phases and the components in the reservoir may induce contamination of the hydrogen stored. The reservoir must be clean of contaminants to ensure safe UHS operation. Significant hydrogen loss can occur when contaminants like methanogenic and sulfate-reducing bacteria are present [47]. Among the most researched subsurface geological porous media are oil and gas reservoirs. Depleted gas reservoirs are particularly easy to handle due to their extensive history of development, management, and operation; their stable caprock and well-documented geological properties make them suitable for UHS. However, before storing hydrogen in these reservoirs, a number of important issues must be resolved, including controlling bacterial hydrogen loss, reducing biological reactions [48] impacted by hydrogen, avoiding cushion gas mixing, and guaranteeing the hydrogen gas's purity during retrieval [45]. A depleted hydrocarbon reservoir offers hydrogen storage, with the cushion gas likely being natural gas. Processes like mixing, bacterial activity, and leakage may occur. The reservoir's depth ranges between 1 and 3 km, and the hydrogen plume extends several kilometers [49]. Hydrogen storage in clathrate hydrate presents a promising avenue for underground storage, particularly in depleted oil and gas reservoirs. This storage method offers several advantages, including storage capacity (up to 5.4 wt.% of hydrogen), enhanced safety due to reduced hydrogen mobility and reactivity, reversibility, and compatibility with existing infrastructure [50]. However, challenges remain, primarily requirements for pure hydrogen clathrate formation (typically above 150 MPa) and slow formation and dissociation kinetics [51]. While hydrogen hydrates show promise for large-scale storage due to their safety, cost-effectiveness, and environmental benefits, further research is needed to overcome pressure and kinematic limitations for practical scalability.

The implementation of underground energy storage (UES) in depleted oil and gas reservoirs requires careful consideration of key geological and engineering specifications to ensure stability and efficiency. Ideal storage sites should consist of large, homogeneous, and isotropic sedimentary rock formations with minimal tectonic deformations and no significant faults, fissures, or discontinuities. Suitable depths range between 70 and 200 m or where groundwater hydrostatic pressure equals or slightly exceeds the storage pressure of hydrogen, carbon dioxide, or natural gas. Low porosity and permeability are essential to prevent leakage, with hydraulic fracture recommended below 10^{-8} ms^{-1}. The site must also exhibit resistance to hydraulic fracturing, maintaining thermal stability within 4 °C and 80 °C, and support a storage lifespan exceeding 30 years. These criteria are crucial for the safe and effective utilization of depleted reservoirs for long-term storage [52].

5.2. Aquifers

Aquifers are subsurface rocks or soil layers containing pore-filled water. Their widespread distribution makes them useful for hydrogen storage. Aquifers are also capable of successfully storing various gases, as multiple studies have demonstrated [53,54]. A low-permeability cap rock must exist above the aquifer to halt gas leakage, and the rock must have high porosity and permeability to allow gas flow in order to store hydrogen in the aquifers. However, faulting, mineral interactions, and chemical or biological activities can cause issues with hydrogen storage in aquifers and decrease storage performance. Furthermore, aquifers are frequently poorly studied compared to depleted oil and gas fields, necessitating extra testing and drilling to minimize risks and uncertainties. An important contrast between depleted fields and aquifers is the cushion gas quantity needed to maintain steady pressure. Aquifers require 80% of cushion gas, whereas depleted fields only require 50% to 60%. Therefore, for aquifer storage projects, selecting a suitable gas type for cushioning is critical. Considering the physiochemical properties of hydrogen, significant funding for subsurface infrastructure, including wells and injection systems, is required to switch from underground gas storage to hydrogen storage in aquifers, enhancing its economic feasibility [53]. Aquifer water can also generate problems such as excessive hydrogen and water generation and alterations to the liquid–gas interface during injection and withdrawal, which can raise prices. Underground hydrogen storage in aquifers must be practical and cost-effective. To achieve this, it is necessary to address the challenges similar to those faced when using depleted reservoirs for storage. Detailed hydrodynamic analysis during storage and recovery cycles is essential to ensure the efficiency of UHS in aquifers. Key factors include the reservoir's ability to store and transmit hydrogen effectively and the presence of a non-permeable barrier to prevent gas leakage.

The use of saline aquifers for underground energy storage (UES) requires adherence to specific geological and engineering criteria to ensure safety and efficiency. Suitable storage formations should primarily consist of sandstones or conglomerates, with caprock composed of shale, siltstone, or carbonate rocks to provide an effective seal. A minimum caprock thickness of 6 m is required to prevent leakage. Optimal storage depth ranges from 200 to 2000 m, while the storage formation should have a porosity greater than 10%, a thickness of at least 300 m, and a vertical closure of no less than 10 m. Additionally, the discovery pressure should range between 2 and 8 MPa to maintain reservoir integrity and storage performance. These specifications are vital for the successful application of UES in saline aquifers [52].

5.3. Salt Caverns

Caverns can be formed in two types of salt deposits: bedded salts and salt domes. Salt domes are thick and uniform masses of salt, making it easy to create a stable cavern for typical operations. Bedded salts are thinner layers found closer to the surface and mixed with other rocks like anhydrite, dolomite, and shale. Nonetheless, if the depth exceeds 6000 ft beneath the ground, the salt may deform due to high pressure and temperature, even if the cavern is well designed [52]. In addition, underground hydrogen storage caverns in formations like bedded salts are less stable and thinner because of the different types of rocks. Salt caverns have advantages and disadvantages compared to porous formations (aquifers and depleted reservoirs) for gas storage. Some disadvantages are their limited availability, the need to manage and dispose of water, the possibility of irregular-shaped caverns, and thermal and mechanical stability challenges. Some advantages are the natural impermeability that prevents leakages and the rapid injection and extraction, which ensure efficient energy management and maintain hydrogen purity and flexible operation at varying pressures. Another factor that affects the injection rate is the amount of water left at the bottom of the cavern, which needs to be considered carefully. Cavern lithology varies across different layers, each with specific properties that influence creep rates, deformation, and sliding behavior along the bedding planes. Caverns can extend to depths of around 2 km and store up to 1 million cubic meters of working gas [51]. Stability and safety concerns are critical variables that constrain the shape, size, spacing, and target pressure levels for both the working and cushion gases. In addition, the creep behavior of creep in rock salt must be assessed before beginning operations. For underground rock formations such as caverns, initial stress is required before construction [51]. Standard operating procedures, conventional practices, and geomechanical evaluations of the location-controlled gas operating pressures are also required. To prevent structural loss from salt hydraulic fracturing and possible failure of the cemented well casing, the maximum pressure is generally kept at 75–85% of the initial vertical starting stress component [51,52].

Salt caverns are a promising option for underground energy storage (UES), offering unique advantages due to their geological and structural properties. Suitable salt formations include bedded salt or salt domes, with caprock typically consisting of anhydrite, gypsum, or limestone. The salt composition should be at least 95% halite to ensure structural integrity. Ideal storage depths range from 200 to 200 meters, with cavern heights typically around 300 m and diameters of approximately 70 m. The maximum salt temperature should not exceed 80 °C to maintain stability. Storage volumes vary depending on the formation type, with salt domes accommodating 300,000 to 750,000 m^3 and bedded salt around 100,000 m^3. The expected storage lifespan ranges from 30 to 50 years, making salt caverns a reliable and efficient option for underground hydrogen storage. These characteristics distinguish salt caverns from other storage types such as depleted reservoirs and aquifers, each offering unique advantages and trade-offs [52].

Underground hydrogen storage is possible in depleted reservoirs, aquifers, and salt caverns, each with advantages and disadvantages. Table 3 compares the underground storage types.

Table 3. Comparison of underground hydrogen storage types [26,51].

Storage Type	Depleted Gas	Aquifer	Salt Cavern
Geographical availability	High in most countries	High in most countries	Limited
Storage capacity	Medium to large	Large to very large	Small to medium
Suitability for hydrogen	Pure hydrogen under study, hydrogen–methane proven	Experience from depleted field still under study	Proven

Table 3. *Cont.*

Storage Type	Depleted Gas	Aquifer	Salt Cavern
Cushion gas requirement	50–60%	45–80%	20–33%
Number of cycles per year	1–2	1–2	10
Chemical conversion rate	Average	High	Low
Operational pressures	15–285 bar	30–315 bar	35–270 bar
Operational type	Seasonal	Seasonal	Frequent
Seismic risk	Average	High	Low
Withdrawal rate	Average	High	Low
Leakage risk	High	High	Low
Total Cost USD/kg	1.43	1.50	0.39–2.41
Development/operation cost	Average	Average	High
Key considerations/factors	Microbial activity, fluid–rock composition, operational conditions	Microbial activity, fluid–rock composition, gas tightness (new storage development)	Salt domes are favored over bedded salt deposits

6. Mechanisms of Underground Hydrogen Storage

UHS involves a complex interplay of geochemical, physicochemical, hydrodynamic, microbial, and biological factors as indicated in Figure 5. The advancement of UHS technology requires a strong understanding of the mechanisms at work throughout time and operational cycles. Many important problems hinder UHS development: controlling hydrogen flow in the porous reservoirs, understanding the possible geochemical reactions during and after injection, addressing microbial interactions leading to hydrogen consumption, and determining how storage affects the geomechanical stability of the formation. Further challenges are limited storage capacity, geological integrity maintenance, and inadequate sites. Ultimately, the viability and potential of UHS depend heavily on the features of the geological formation.

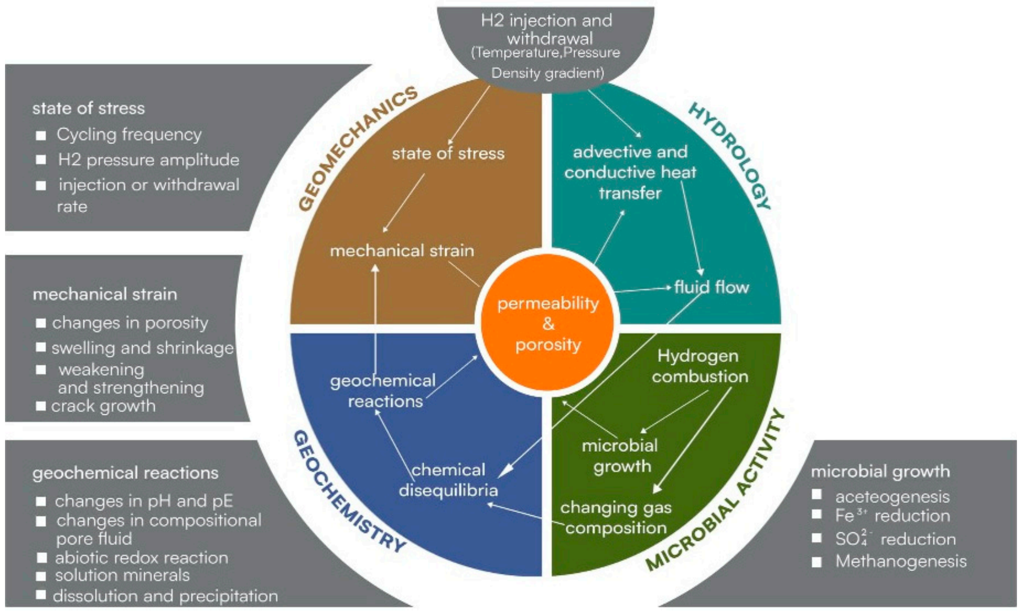

Figure 5. Scientific challenges of hydrogen storage in porous media.

6.1. Geochemical Activities

Hydrogen reactivity can produce harmful gases that impact the wellbore, soil, and atmosphere, affecting UHS systems' sustainability and long-term material lifespan. During UHS, geochemical interactions between reservoir fluids, cushion gas, hydrogen gas, and reservoir minerals may occur. These reactions deplete hydrogen by converting it to hydrogen sulfide (H_2S) and methane (CH_4). In addition, geochemical reactions can lower the hydrogen purity by combining it with other reservoir gases. The quality of hydrogen may be affected by residual gases in depleted reservoirs or gases produced over time via hydrogen-related reactions, regardless of storage conditions. Geochemical activity during UHS can lead to mineral precipitation or dissolution, altering permeability and porosity, and potentially causing structural collapse or faults in the cap rock integrity [26]. Geochemical processes involve both biotic and abiotic reactions, with abiotic reactions involving interactions between non-living molecules like oil, gas, brine, rock minerals, and hydrogen [55]. Abiotic reactions, including mineral precipitation, dissolution, equilibrium, and ion exchange, can significantly influence the mineral makeup of formation fluids over time, as highlighted by [56]. The study reveals that hydrogen may slightly dissolve in fluids upon injection, which could lead to hydrogen contamination with water vapor due to chemical disequilibrium. Additionally, hydrogen trapping due to capillary forces and hydrogen adsorption by clay minerals can progressively degrade the reservoir and caprock integrity [54]. In high-temperature conditions with hydrogen present, undesirable geochemical reactions can release toxic gases and cause changes in the water pH, further accelerating mineral dissolution. Studies [57,58] reveal that hydrogen solubility decreases under high-temperature and high-salinity conditions, indirectly influencing mineral dissolution but not significantly altering the native chemical makeup of formation fluids. These findings underscore the need for further investigation into the hydrogeochemical interactions within UHS to ensure safe and efficient storage. The study in [59] reveals that hydrogen losses due to bacterial and hydrogeochemical interactions are influenced by factors such as co-injected CO_2 and sulfate in the reservoir. They noted that extended storage periods increased the risk of hydrogen loss, particularly because of the higher propensity for methanogenesis when CO_2 is co-injected. However, over time, mineralogical attenuation through the consumption of anhydrite and calcite reduces the impact of bacterial processes like sulfate reduction and methanogenesis, leading to safer storage conditions [60]. Table 4 indicates the possible geochemical reactions in UHS.

Table 4. Comparison of possible geochemical reactions during UHS [61–64].

Variables **Abiotic Reactions**		**Log K at 298.15 K and 1 Bar**
Primary Minerals	Dissolution and Precipitation	
	Carbonates	
Calcite	$CaCO_3 + 5H_2 \leftrightarrow Ca^{2+} + CH_4 + 3H_2O + 2e^-$	
Dolomite	$CaMg(CO_3)_2 + 10H_2 \leftrightarrow Ca^{2+} + Mg^{2+} + 2CH_4 + 6H_2O + 4e^-$	8.47
Magnesite	$MgCO_3 + 4H_2 \leftrightarrow Mg^{2+} + CH_4 + 2OH^- + H_2O$	−17.09
Siderite	$FeCO_3 + 4H_2 \leftrightarrow Fe^{2+} + CH_4 + 2OH^- + H_2O$	
Dawsonite	$NaAlCO_3(OH)_2 + 3H^+ \leftrightarrow Al^{3+} + HCO_3^- + Na^+ + 2H_2O$	4.35
	Sulfide	
Pyrite	$FeS_2 + 2H^+ + 2e \leftrightarrow Fe^{2+} + 2HS^-$	18.48
	Sulfate	
Anhydrite	$CaSO_4 + 5H_2 \leftrightarrow Ca^{2+} + H_2S + 4H_2O + 2e^-$	−4.39
Celestite	$SrSO_4 + 4H_2 \leftrightarrow Sr^{2+} + H_2S + 2OH^- + 2H_2O$	−6.63
Barite	$BaSO4 + 4H_2 \leftrightarrow Ba^{2+} + H_2S + 2OH^- + 2H_2O$	−9.97
	Fe^{3+} Oxides	
Hematite	$Fe_2O_3 + H_2 + H_2O \leftrightarrow 2Fe(OH)_2$	
K-Feldspar	$KAlSi_3O_8 + 8H_2O \leftrightarrow K^+ + Al(OH)^{4-} + 3H_4SiO_4$	−20.573

Table 4. *Cont.*

Variables **Abiotic Reactions**		**Log K at 298.15 K and 1 Bar**
Secondary Minerals	Clay Minerals	
Kaolinite	$Al_2Si_2O_5(OH)_4 + 6H^+ \leftrightarrow H_2O + 2H_4SiO_4 + 2Al^{3+}$	7.436
Illite	$K_{0.6}Mg_{0.25}Al_{2.3}Si_{3.5}O_{10}(OH)_2 + 11.2H_2O \leftrightarrow 0.6K + 0.25Mg^{2+} + 2.3Al(OH)^{4-} + 3.5H_4SiO_4 + 1.2H^+$	−40.27
	Silicate Minerals	
Quartz	$SiO_2 + 2H_2O \leftrightarrow H_4SiO_4$	3.96
Albite	$NaAlSi_3O_8 + 8H_2O \leftrightarrow Na^+ + Al(OH)^{4-} + 3H_4SiO_4$	−18
Biotic Reactions		
	$H_2O \leftrightarrow H^+ + OH^-$	−14.2
	$Al^{3+} + 4H_2O \leftrightarrow Al(OH)^{4-} + 4H^+$	−22.8
	$2CO_3^{2-} + Ca^{2+} \leftrightarrow CaCO_3$	1.28
	$CO_3^{2-} + Mg^{2+} \leftrightarrow MgCO_3$	3.22
	$HCO_3 + Na^+ \leftrightarrow NaHCO_3$	11.94

The current experimental findings indicate that geochemical effects are probably negligible when microbial activity is absent. The study in [58] exposed sandstones to hydrogen gas in a batch experiment; however, they found no indication of reactions or significant changes in the petrophysical characteristics of the samples, such as their porosity or specific surface area. Moreover, a recent study comprising 250 batch trials on diverse sandstone samples indicated that pure geochemical reactions impact underground hydrogen storage (UHS) reservoirs less. This was because fluid chemistry revealed minor variations between hydrogen-rich and nitrogen-rich environments over two months [65]. Figure 6 shows the background of the main reactions and processes involved in bacterial sulfate reduction and methanogenesis (marked in purple). Kinetically controlled reactions are represented by single arrows, whereas equilibrium reactions are shown with double arrows. The blue triangles indicate the diffusion of aqueous components over time, while bold text highlights the injected gas used for storage.

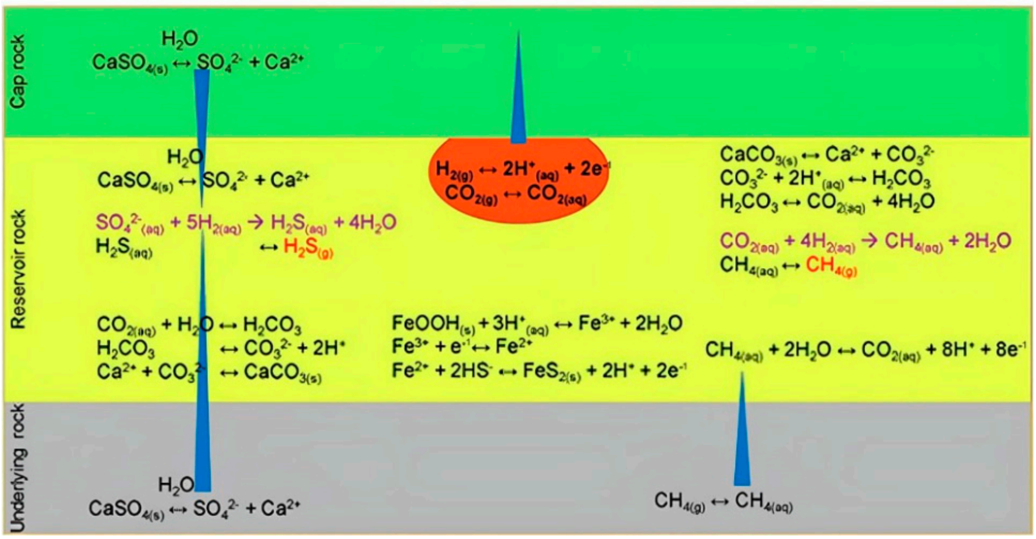

Figure 6. Possible geochemical reactions (adapted and modified from [59]).

6.2. Microbial Activity

Hydrogen can cause embrittlement in the auxiliary parts of the rock caverns, such as compressors, pipes, and steel linings. Finding glaring flaws at every location is crucial, particularly for hydrogen consumption through homoacetogenesis, sulfate reduction, and methanogenesis. The fact that certain microbes can consume hydrogen at rates of up to 4533 nM per hour emphasizes the need for proper site selection. Iron-rich strata are more appropriate for UHS, and the current storage locations in rock caves may need to be modified. Generally, sulfate, carbonate, or sulfide rocks should be avoided [26]. Many features of microbial interactions are currently poorly understood and understudied. Therefore, more research is required to build effective prediction tools for hydrogen consumption and microbial growth in various geological hydrogen storage systems. In particular, studies aimed at establishing crucial parameters—such as salinity, temperature, and pressure—may yield significant new insights into the dynamics of microbes. Early research indicated that sulfate reducers, homoacetogens, methanogens, and bacteria that reduce iron (III) grow in the pH range of 6–7.5. These bacteria thrive in salinity ranges below 60 < 100 < 40 and 40 g/L^{-1}, respectively. Optimal temperature ranges for these microorganisms vary: sulfate reducers and homoacetogens thrive at 20–30 °C, methanogens prefer 30–40 °C, while iron (III)-reducing bacteria perform best at 0–30 °C [66]. When H_2 is stored underground, increased H_2 concentrations can stimulate microbial activity in subsurface environments, leading to adverse effects like reservoir weakening, infrastructure corrosion, H_2 losses, reduced permeability, and potential fault activation. These interactions vary with the geological storage type, where depleted hydrocarbon reservoirs and saline aquifers are more prone to these effects than salt caverns. Research has emphasized the importance of microbial activity but has not provided numerical insights into the impacts of higher H_2 levels in saline and alkaline environments [26]. Consequently, the biological consumption of H_2 in hydrocarbon reservoirs and aquifers becomes inevitable and undesirable. It is advised that H_2-driven reduction in acetate and sulfate occur gradually in gas reservoirs and acidic, high-salinity aquifers owing to the reaction patterns. However, H_2 may also react with hydrocarbons in the same medium, which could result in H_2 depletion. The presence of sulfur further exacerbates this issue, as H_2 can form hydrogen sulfide (H_2S), resulting in economic losses and posing safety risks for storage operations. Generally, four main categories of microbial activity must be considered in geological H_2 storage: methanogenesis, acetogenesis, sulfate reduction, and iron reduction [28,66]. There is evidence of potential microbial activity within the UHS, as illustrated in Table 5.

Table 5. Microbial activity for underground hydrogen storage [66–68].

Variables Primary	**Reservoir, Caprock, and Wellbore**	**Free Energy (kJ/mol)**
Methanogenesis	$CO_2 + 4H_2 \leftrightarrow CH_4 + 2H_2O$	−33.9
Acetogenesis	$2CO_2 + 4H_2 \leftrightarrow CH_3COOH + 2H_2O$	−26.1
Iron reduction	$2Fe^{3+} + H_2 \leftrightarrow 2Fe^{2+} + 2H^+$	−228.3
Sulfate reduction	$SO4^{2-} + 5H_2 \leftrightarrow H_2S + 2H_2O$	−38.0
Secondary		
Denitrification	$2NO^{3-} + 5H_2 + 2H^+ \leftrightarrow N_2 + 11H_2O$ $7C_6H_{12}O_6 + 6NO_3^- + 6H^+ \leftrightarrow 6C_5H_7O_2N + 12CO_2 + 24H_2O$	
Heterotrophic Biomass synthesis	$2C_3H_8O_3 + NO_3^- + H^+ \leftrightarrow C_5H_7O_2N + CO_2 + 5H_2O$ $7CH_3COOH + 2NO_3^- + 2H^+ \leftrightarrow 2C_5H_7O_2N + 4CO_2 + 8H_2O$ $14H(CH_2)_nCOOH + (3n+1)\,NO_3^- + (3n+1)\,H^+ \leftrightarrow (3n+1)$ $C_5H_7O_2N + (9-n)\,CO_2 + (5n+11)\,H_2O$	

Microorganisms catalyze H_2 conversion and are influenced by microbial concentration, equilibrium constant, enthalpy, and water chemistry, such as temperature and salinity. Key parameters impacting microbial development during methanogenesis include temperature (optimal: 30–40 °C, critical: up to 122 °C), salinity (optimal: <60 g/L, critical: up to

200 g/L), pH (optimal: 6.0–7.5, critical range: 4.5–9.0), low redox potential, and medium CO_2/carbonate content. In UHS, microbial methanogenesis can affect operations through hydrogen consumption at rates of 0.0008–0.58 mM/h, leading to hydrogen loss as compounds like CH_4, CH_3COOH, H_2S, or Fe (II) are produced. This process can also result in altered permeability, pH reduction, corrosion, hydrogen embrittlement, pore-clogging, mineral dissolution, and precipitation, ultimately impacting the injection and retrieval capacity. Monitoring these factors is crucial for maintaining storage efficiency and infrastructure integrity [69]. In underground hydrogen storage, acetogenesis can consume hydrogen at rates of 0.02–0.5 mM/h, posing risks of hydrogen loss as acetate is produced. The three main variables affecting microbial development during acetogenesis are pH (optimal: 6.0–7.5, critical range: 3.6–10.7), salinity (optimal: <40 g/L, critical: up to 300 g/L), and temperature (optimal: 20–30 °C, critical: up to 72 °C) [66]. Acetogenesis increases the risks of leakage and water saturation, which may affect storage conditions. Managing these parameters is essential for reducing hydrogen loss and maintaining stable storage conditions. Iron reduction in underground hydrogen storage can consume hydrogen at 0.0005–0.22 mM/h, contributing to hydrogen loss as iron is reduced. Microbial growth during iron reduction is influenced by temperature (optimal: 20–30 °C, critical: up to 113 °C), salinity (optimal: <100 g/L, critical: up to 240 g/L), pH (optimal: 6.0–7.5, critical range: 0.8–11.5), and sulfate mineral content. Key factors affecting microbial activity in iron reduction include temperature (optimal: 0–30 °C, critical: up to 90 °C), salinity (optimal: <40 g/L, critical: up to 200 g/L), pH (optimal: 6.0–7.5, critical range: 1.6–9.0), and the presence of iron minerals. Monitoring and controlling these conditions are vital to reduce hydrogen loss and ensure stable storage conditions [66–70].

6.3. Hydrodynamic Phenomena

Hydrogen storage in porous reservoirs involves complex fluid interactions, with the injected hydrogen pushing out existing brine or hydrocarbons. These interactions are influenced by fluid properties, reservoir rock characteristics, and phase interactions [65]. However, there is still a limited understanding of how H_2 behaves in these environments, as there has been minimal experimental research under actual reservoir conditions. In contrast to gases such as methane (CH_4) or carbon dioxide (CO_2), H_2 presents distinct challenges in porous reservoirs due to its low density and viscosity [65]. These properties can lead to issues like gravity segregation, unstable flow, and lateral spreading, making recovering some of the injected hydrogens difficult. Hydrogen is also prone to mixing with cushion gases and any remaining hydrocarbons in depleted oil and gas reservoirs. These mixing effects, and how H_2 moves in the reservoir, are critical for maintaining hydrogen purity, storage efficiency, and reliable recovery over long periods and multiple injection and withdrawal cycles. Whether H_2 flow is miscible or immiscible depends on the reservoir type. In aquifers, for example, the absence of a cushion gas can create conditions where capillary trapping and viscous fingering occur, which can trap hydrogen and reduce the efficiency during withdrawal. In depleted oil and gas fields, where miscible flow is more likely, hydrogen can mix with existing gases, reducing the purity of the hydrogen recovered. These flow dynamics are key factors to examine the viability and efficiency of underground hydrogen storage [21,22].

6.3.1. Interfacial Tension Between Hydrogen and Fluids

A clear understanding of interfacial tension (IFT) between hydrogen and other fluids is essential for analyzing the flow behavior of hydrogen in subsurface storage. For hydrogen–brine systems, IFT has been measured experimentally as 72.3 $mN{\cdot}m^{-1}$ under pressure of 0.5 MPa and room temperature against hydrogen–carbon dioxide–brine, which is 72.0 mN·m^{-1} at the same conditions, but decreases with higher pressure and temperature, reaching 66.8 mN·m^{-1} at 25 MPa and 50 °C. Similarly, in hydrogen–carbon dioxide–brine systems, IFT drops significantly from 72.0 to 33.3 mN·m^{-1} at 44.7 MPa and 73 °C [65]. Unlike hydrogen–brine systems, increased brine salinity does not raise hydrogen–brine IFT. IFT influences multiphase flow by controlling capillary forces, which affect flow patterns like stable flows or fingering phenomena [71,72].

6.3.2. Wettability Behavior Under Hydrogen Conditions

The wetting properties of reservoir rock significantly affect fluid displacement during hydrogen storage, especially as different fluids interact within the reservoir. Hashemi et al. examined hydrogen–methane interactions involving sandstone and brine at various salinities, pressures, and temperatures and they found that sandstone wettability remains largely unchanged by hydrogen [72]. Other studies have shown that brine shows a stronger wetting phase than hydrogen, particularly in sandstones, where injected H_2 tends to flow through larger pores whereas brine occupies smaller pores under higher capillary pressures. Additionally, studies by Iglauer et al. demonstrated that hydrogen on quartz surfaces exhibits lower wettability than CO_2, a trait beneficial for hydrogen storage, as it allows H_2 to stay as a mobile, easily retrievable phase within the reservoir [65,73].

6.3.3. Relative Permeability

Relative permeability studies for hydrogen–brine systems highlight how fluid interactions and rock properties affect hydrogen flow efficiency in subsurface storage. Drainage and imbibition curves at room temperature and pressures reveal hysteresis effects that reduce hydrogen withdrawal efficiency. Additionally, minimal crossover points indicate flow interference between the relative permeabilities of brine and hydrogen when both fluids move simultaneously [65]. The study in [74] conducted unsteady-state research and showed that the relative permeability of the hydrogen decreases at high pressures (10.34 MPa and 20.68 MPa) due to the increase in hydrogen viscosity. The study found that increased rock porosity increases hydrogen permeability, indicating that more porous rocks improve hydrogen flow. Although these insights are valuable for hydrogen storage in saline aquifers, research on how hydrogen interacts with cushion gases and residual hydrocarbons in depleted oil and gas reservoirs requires extensive research [65,72]. The studies in Refs. [65,75] found that adding 50% CH_4 as a cushion gas to H_2 improves gas relative permeability by 70.5%. This indicates better displacement efficiency because of the decreased gas–brine interfacial tension and increased gas viscosity. Studies on other cushion gases like nitrogen and CO_2 would further inform optimal cushion gas choices for efficient hydrogen storage.

6.3.4. Displacement and Fingering Phenomena

Porous hydrogen storage faces challenges due to unstable displacement; this instability, known as density fingering, occurs due to variations in fluid viscosity. Viscous fingering, a phenomenon where hydrogen moves unevenly, increases the risk of residual trapping and hydrogen dissolution in the brine, thereby reducing hydrogen recovery efficiency. Early research on UHS in 1982 revealed fingering [76]. Direct experiments are crucial for understanding multiphase flow in porous reservoirs. Recent hydrogen–brine displacement experiments for water-wet reservoirs on sandstone samples confirmed that residual brine occupies pore corners and throats, whereas hydrogen flows centrally within pores. The findings affirm that capillary fingering patterns are dominant in multiphase hydrogen–brine systems, mainly due to the significant interfacial tension between hydrogen and brine at low flow rates in the experiments. High hydrogen–brine interfacial tension favors capillary fingering, which occurs when capillary forces exceed viscous forces, specifically when the capillary number falls below a critical threshold, generally between 10^{-6} and 10^{-4} [65,77]. This unstable displacement forms finger-like paths that lead to hydrogen loss. The interaction between hydrogen and brine is influenced by the flow rate; higher flow rates reduce capillary fingering but increase viscous fingering. Experiments and simulations on multiphase hydrogen–brine displacements provide valuable insights into improving underground hydrogen storage (UHS) by optimizing recovery and minimizing hydrogen loss [65].

6.3.5. Dissolution of Hydrogen in Brine

Carden and Paterson theorized that hydrogen dissolution in brine during underground storage is minimal, with less than 2% of injected hydrogen dissolving [78]. However, experiments have highlighted the significant impact on phase behavior and hydrogen recovery. Jangda et al. found that injecting hydrogen into non-equilibrated brine could result in up to 7% dissolution, reducing residual saturation compared to equilibrated brine [79]. Boon and Hajibeygi also revealed that hydrogen dissolution into non-equilibrated brine could lead to miscible displacement [77]. Lysyy et al. observed non-equilibrium dissolution through imaging, with dissolved hydrogen at a level averaging 16%, which is below the equilibrium solubility of 28.3% and could limit hydrogen loss [80]. Meanwhile, Amiri et al. showed that cushion gas choice impacts recovery, with CO_2's high solubility lowering recovery efficiency compared to CH_4 or N_2. Further studies, especially core flooding experiments, are needed to better understand and optimize hydrogen recovery in brine systems [81].

6.3.6. Residual Trapping

Experimental investigations have identified residual hydrogen trapping in rock due to fluid redistribution after drainage and shut-in phases. This results in hydrogen clusters in the pore spaces, limiting hydrogen recovery and potentially causing loss. Since 1915, the idea of gas storage in depleted reservoirs has been around, and the behavior of H_2 in subterranean formations has been understood through comparisons with natural gas and CO_2 geo-storage. Four techniques have been identified in maintaining gas in subsurface formations: mineral trapping, solubility/dissolution, residual/capillary, and structural/stratigraphic. Whereas residual/capillary trapping is typical in sedimentary formations, structural/stratigraphic trapping is common in caprock and sedimentary formations [76,77]. The trapping mechanism in sedimentary rocks is based on wettability, where rocks prefer a specific phase. This wettability affects residual trapping and helps identify the interaction of H_2 with brine in reservoir and storage rock. The Young–Laplace equation can be used to estimate the capillary forces that retain the buoyant H_2 gas within the capillary pores. Hysteresis is a fundamental feature of multiphase flow and forms the basis for the trapping mechanism. This mechanism significantly assists in quantifying the amount of gas migration as well as the distribution in the formation, thereby influencing the efficiency of other trapping mechanisms [65,77]. Hydrogen trapping in water-wet reservoirs is affected by various factors such as capillary number and flow rates. Higher injection rates increase the initial gas saturation, whereas higher imbibition rates reduce the residual gas saturation, promoting hydrogen recovery. Multiple injection–withdrawal cycles enhance gas recovery, with secondary drainage improving recovery. Larger injection and withdrawal flow rates improve recovery, but residual trapping can cause losses of up to 40% during withdrawal. Optimizing the flow rates and cycles significantly enhances the hydrogen extraction efficiency.

6.4. Geomechanical Considerations

The geomechanical elements affecting underground hydrogen storage (UHS) are described in this section. The reaction of the reservoir rock to UHS conditions is primarily influenced by the rate of injection and production, the structure of the wellbore, rock tensile strength, and the existence of fractures or faults [26]. Repeated cycles of gas injection and withdrawal during hydrogen storage affect the formation's effective stress because of fluctuations in pore pressure, which threatens the reservoir and caprock's integrity. Geomechanical modeling considers geomechanical repercussions such as fault reactivation, wellbore and cap rock stability, and probable reservoir fracture. Geochemical interactions may be the source of this degradation, as the dissolution of minerals in the rock increases the probability of gas escape. Furthermore, cyclic stress variations caused by H_2 injection and withdrawal may reactivate fractures and flaws, enhancing the risk of leaks and losses even more [55,65]. Therefore, it is vital to understand changes in rock strength, elasticity, and strain under different loads to evaluate how the reservoir formation might geomechanically behave in response to UHS. Because of this knowledge, geomechanical changes can be modeled more precisely to ensure reservoir integrity throughout UHS operations. During underground hydrogen storage, injection and withdrawal cycles cause reservoir pore pressure and temperature to vary, which can introduce significant risks during and after operations. These risks include potential reductions in rock strength, ground subsidence or uplift, compromised well integrity, persistent hydrogen leakage, reduced effectiveness of the caprock seal, and seismicity due to fault reactivation. Storing hydrogen in salt caverns poses additional hazards, such as excessive cavern shrinkage (which reduces storage capacity), roof failure, fluid leakage, and other unforeseen issues. Caverns with intricate structures, thick heterogeneous layers, or interactions among multiple caverns within the same geological area present additional challenges for UHS. Because both depleted reservoirs and salt caverns rely on wells for hydrogen injection and withdrawal, maintaining wellbore integrity is essential to prevent hydrogen leakage and ensure the safety and efficiency of the storage system [82]. Table 6 compares natural gas, CO_2, and hydrogen storage's subsurface mechanical responses, highlighting the importance of geomechanical study in predicting stress distribution, deformation, and sealing integrity for safe and effective storage across all gases.

Table 6. Geomechanics-based comparison of natural gas, CO_2, and H_2 storage [83].

Storage Type	Natural Gas Storage	UHS	CCS
Conditions of operation	Longer-term cyclic natural gas injection and projection.	Cyclic injection and production of H with higher frequency and mobility can pose unknown operation challenges and progressive damage to rocks due to intergranullar swelling and cycles.	Continuous CO_2 injection into the salt cavern and depleted reservoirs can act as cushion gas for UHS, which guarantees steady pressure after injection.
Potential hazards	Depending on the chosen reservoir site and operational conditions, natural gas storage sites may experience induced seismicity, fracture propagation, and subsidence/uplift.	Ground subsidence/uplift, caprock integrity, and seismicity can all be accelerated by cyclic loads. Similar to creep, elastic deformation can speed movement along pre-existing faults.	Depending on the selected reservoir site operating conditions, CCUS may undergo induced seismicity, fracture propagation, and subsidence/uplift.
Mechanism of well integrity	Comparatively minimal hazard of hydrogen blistering, cement carbonation, and corrosion depending on the reservoir site chosen.	Steel corrosion, hydrogen blistering, and sulfidation are all threatened by ambient hydrogen, which may also induce elastomer degradation.	The presence of carbonic acid may lead to corrosion, cement carbonation, and elastomer disintegration.
Risk of leakage	Caprock leakage is less likely in methane water systems with higher interfacial tensions.	Mineral dissolution alters reservoir and caprock properties, leading to permanent deformation and low fault slip threshold, H_2 percolation, and hydraulic fracturing, and salt creep accelerates fault slip.	Fault opening and seal failures can both result in leaks. Rock porosity and permeability can be modified using CCS in an environment that is corrosive and has a low gas–water interfacial tension. Depending on the cavern's operational limits and heterogeneity, leakage may occur from salt cavern roof failure.

7. Modeling Strategies for Underground Hydrogen Storage

Geochemical, geomechanical, and hydrodynamic interactions influence UHS, which is a complicated process affecting the injection, storage, and generation of hydrogen gas. Forecasting UHS performance requires knowledge of these pathways. Important qualities and considerations include rock, fluid, operational, geomechanical, reservoir, and microbiological environments. Many modeling approaches have been presented to evaluate these implications; Figure 7 below presents the key features and related factors.

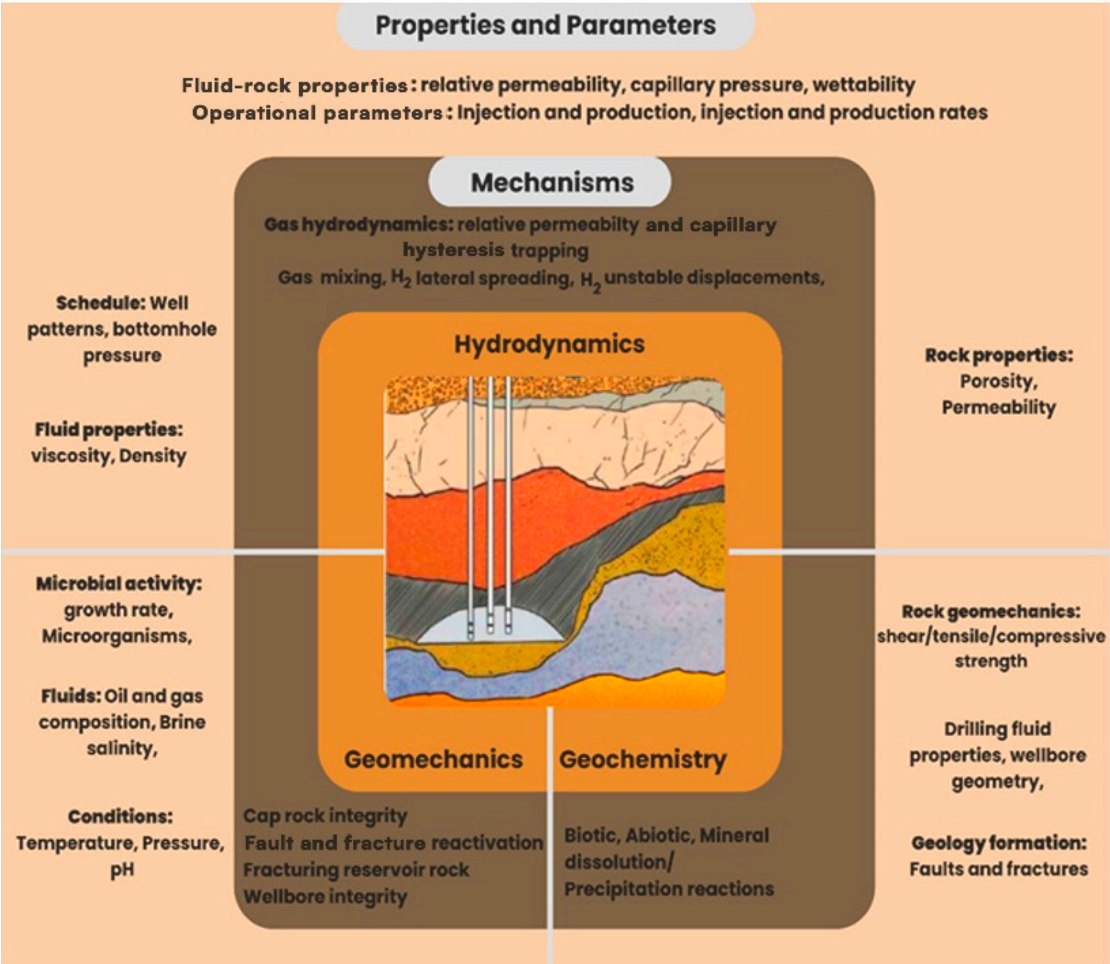

Figure 7. Mechanisms influencing modeling of UHS.

Geochemical modeling is important for comprehending and mimicking the numerous processes involved in underground hydrogen storage (UHS). The models must capture equilibrium processes and precipitation and mineral dissolution reactions. Among the elements impacting the rates of these kinetic reactions are temperature, pressure, and salinity [59]. Because of this, modeling methodologies that apply constant reaction rates could result in erroneous predictions. Additionally, conditions are necessary for validating and calibrating reaction rates and eventually enhancing the precision of geochemical models for UHS. Geochemical research investigates how hydrogen interacts with different minerals in reservoirs and the brine composition of the reservoir. Table 7 summarizes geochemical modeling strategies undertaken for underground hydrogen storage.

Table 7. Summary of selected geochemical modeling methods for underground hydrogen storage.

Storage Formation	Purpose	Software Approaches	Comments	Sources
Depleted gas reservoir	Assessment of the impact of geochemical reactions in UHS	PHREEQC version 3	The majority of hydrogen loss results from biotic reactions, which are controlled by kinetic reactions.	[57]
Sandstone Reservoir	Impact of geochemical processes that were triggered during UHS	Geochemist Workbench for Geochemical modeling	Aqueous—phase and hydrogen equilibrium process are More prevalent during the storage–relevant time period	[59]
Aquifer	Investigation of how hydrogen oxidation reduction processes work in UHS	PHREEQC for geochemical modeling	Sandstone rocks are favored options over carbonate minerals during UHS since carbonates can initiate more H2 Dissociation and redox processes, making them reactive	[62]
Carbonate reservoir	Assessment of how different reservoir factors affect hydrogen—calcite system wettability	PHREEQC DLVO theory	Increasing the pressure and lowering the salinity can enhance the disjoining pressure within the hydrogen-brine-calcite system	[62]
Depleted gas reservoir	Assessment of how caprock integrity is affected by geochemical reactions during UHS	PHREEQC for geochemical modeling	The integrity of the seal is protected from the H2 brine–rock geochemical interactions because of minimal shale mineral dissolution.	[84]
Majiagou carbonate reservoir	Examination of how the geochemistry of carbonate affects UHS	PHREEQC 3.7.1	After 500 years of storage hydrogen loss from the fluid-rock composition is predicted to reach 81.1%, while in the first year, it could reach 6.6%	[84]
Depleted gas reservoir	Examination of hydrodynamic and biochemical behaviors during UHS	Numerical modeling with DuMuX coupled with biochemical modeling	The presence of microorganisms in the reservoir substantially affects the process of hydrogen conversion into methane.	[85]
Salt cavern	Investigating geochemical impact of UHS in salt cavern	PHREEQC	Ionic strength, temperature, PH, and cave pressure all impact bacterial growth with iron ions being the most crucial factor influencing hydrogen production from hydrogen	[85]
Sandstone reservoir and carbonate reservoir	The study uses geochemical modeling to assess hydrogen losses within a sandstone reservoir	PHREEQC 3.7.3	Temperature and pressure have little effect on hydrogen loss because of solubility. For storing hydrogen, a sandstone reservoir would be preferable to a carbonate reservoir.	[86]

Predicting geomechanical changes during UHS requires determining hydrogen gas injection and production stresses on reservoir rock and establishing rock behavior in terms of deformation, strength, and elasticity. The fluid conservation of momentum equation is used mostly in modeling the geomechanical differences in our formation.

$$p\left(\frac{dv}{dt}+v\cdot\nabla v\right)=-\nabla p+\mu\nabla^2 v \tag{5}$$

The fluid velocity is represented by v in this fluid conservation of momentum equation, accounting for the pressure gradient, ∇p, which can be used to describe the fluid flow behavior of the fluid flow during H_2 injection and production [87]. The Biot equation correlates between rock and fluid and is essential for computing the pressure gradient [26]. The Biot equation is as follows:

$$\sigma' = \sigma - \beta\rho \tag{6}$$

where σ', σ, ρ (pore pressure), and β (Biot coefficient) represent the effective and total stresses, respectively. The main equation used to analyze UHS geomechanical effects is the Hooks law, which describes rock elasticity and matrix deformation by stress and strain.

$$\sigma = E\epsilon \tag{7}$$

Geomechanical modeling systems are crucial for assessing the stability, sealing integrity, and mechanical behavior of underground hydrogen storage reservoirs under cyclic injection and withdrawal. Table 8 summarizes the selected geomechanical models for UHS.

Table 8. Summary of the selected geomechanical models for underground hydrogen storage.

Storage Formation	Purpose	Software Approaches	Comment	Sources
Salt cavern	Evaluates the geochemical impact of UHS	OpenGeoSys	Tensile strains at the cavern barrier may rise as a result of significant temperature amplitude in the working gas.	[88]
Salt cavern	Examines the heterogeneity in the deformation of the salt caverns and quantifies the surrounding state stress	Created an open 2D finite element simulator	Creep in salt caverns occurs gradually and is not influenced by the short-term storage of hydrogen. The heterogeneity of the salt cavern impacts its elasticity in varying ways, depending on the type (potash or halite) and the distribution of impurities.	[89]
Salt cavern	Evaluates the geochemical impact of UHS	Thermo-hydro-mechanical (THM) coupled simulator FLAC3D-TOUGH2MP	The convergence volume of a salt cavern does not influence its storage capacity and the resulting surface subsidence rate is unlikely to cause any damage to surface structures.	[90]
Salt cavern	Assesses the integrity of salt caverns	Numerical modeling	Deeper caverns face greater stability challenges than shallower ones, especially during daily operational cycles; however, gas leakage is generally minimal due to dominant diffusion transport, despite differences in permeability.	[91]
Saline aquifer	Evaluates the hydro-mechanical power aspect of UHS in a river basin in Wyoming state	3D coupled hydro-mechanical model, Peng–Robinson equation of state	Up to 75% of the hydrogen can be recovered by the end of the third cycle and the examination structure remains geomechanically stable. The likelihood of failure also decreases during the withdrawal phase.	[92]

A 3D hydro-mechanical model was created to assess the practicality of underground hydrogen storage (UHS) in Wyoming's Powder River Basin by Bai and Tahmasebi. They employed a one-way coupling technique to predict how rock stress would react to changes in pore pressure and computed hydrogen properties using the Peng–Robinson equation. They found that 75% of the hydrogen could be recovered by the third cycle, and the geomechanical stability was confirmed using the Mohr–Coulomb criterion [92]. Ref. [90] demonstrated that short-term storage at the Anning salt mine in China met safety requirements without issues like surface subsidence, creep, or spalling. The study in [88] proposed fewer storage cycles to limit the tensile stress, which can be increased by large temperature variations at the cavern margins. The study in [89] researched the effects of salt cavern heterogeneity on elasticity and found that while impurities cause localized deformation, cavern creep is not affected by short-term hydrogen storage. Their stability study of shallow and deep caves [91] found that deeper caverns suit intense green hydrogen storage because they have more stability issues but fewer gas losses. Considering hydrodynamic modeling in UHS as indicated in Figure 7 it is necessary to understand the fluid flow within storage formations. Rock factors such as porosity and permeability, fluid properties such as density, viscosity, interfacial tension, solubility, and diffusivity, and rock–fluid interactions under reservoir conditions all influence the behavior of fluid flow in storage [93]. It is vital to incorporate these parameters into hydrodynamic models to appropriately estimate UHS performance.

Software tools like Eclipse, DuMux, CMG-GEM, TOUGH, and COMSOL are commonly applied in underground hydrogen storage to model hydrogen flow and apply fluid flow concepts [55]. An open-source simulator called DuMux can be modified with various equations of state to control the transport of multiple phases and components within the porous media [94–97]. In oil and gas reservoir modeling, SLB's Eclipse software (100 and 300) is extensively used; Eclipse 100 employs a black oil model, while CMG-GEM and Eclipse 300 use compositional models to account for phase behavior differences in fluid compositions. TOUGH is ideal for hydrogen and cushion gas injection since it is made to reflect gas injection and reactive transport [96]. Finally, COMSOL Multiphysics is a versatile simulation tool for chemical reactions and fluid flow [95]. Table 9 reviews a summary of selected hydrodynamics models for underground hydrogen storage.

Table 9. Summary of selected hydrodynamic models for underground hydrogen storage.

Storage Formation	Purpose	Software Approaches	Comments	Sources
Aquifer	Evaluates the role of cushioning gas during UHS	CMG-GEM	The efficiency of hydrogen recovery is increased by cushion gas' cushion gas density and hydrogen recovery efficiency were directly correlated, meaning lighter gases led to an increase in hydrogen recovery Higher hydrogen retrieval was achieved with CH_4 than with N_2 and CO_2.	[55]
Depleted oil reservoirs	Evaluates the impact of various cushion gas types on UHS in depleted oil reservoirs using numerical simulation	CMG-GEM	Up to 15.5% of the stored hydrogen is lost when UHS is used without cushion gas. Compared to carbon dioxide and nitrogen, methane produced greater recovery. For better sweeping of reservoir fluids, an increased rate of hydrogen injection at brief intervals reduces the effects of gravity segregation.	[98]
Salt cavern	Investigates H_2 storage capacity and viability	$AusH_2$	The findings indicated that Australia could develop 28,282 onshore salt caverns with a total capacity of 14,697 PJ of hydrogen energy.	[99]
Depleted gas field	Hydrodynamic numerical simulation during UHS	CMG simulation suite	Higher hydrogen production is a result of lighter cushion gases. Diffusion of hydrogen is negligible	[99]
Deep aquifer	Assesses how the first period affected UHS	PetraSim and TOUGH2	A longer initial filling time led to better overall performance and operational storage capacity.	[100]
Depleted gas	Evaluates the viability of UHS reservoir	TOUGH	Diffusion-induced H_2 loss is negligible (<1%). When N_2 or CO_2 is used as cushion gases, hydrogen recovery is greatly enhanced.	[101]
Depleted gas Condensate reservoir	The study explores the effects of cushion gas in a partially depleted gas condensate reservoir	Adaptive Implicit Mode (AiM)	Due to the alternating trapping gases in the condensate, H_2 recovery was higher in the gas condensate reservoirs. Using nitrogen gas, a cushion during injection resulted in H_2 recovery. Because of molecular diffusion, gas mixing was more noticeable in the early phase of the operation.	[102]
Depleted gas Reservoirs	Multi-scale simulation of (unconventional) UHS)	Numerical modeling using in-house reservoir simulator $MSCO_2$ and Monte Carlo simulation	Because of the distinct adsorption effects of nanopores, hydrogen stored in reservoirs maintains a higher purity than the conventional reservoirs where the majority of the H_2 is still contained in hydraulically cracked areas in the reservoir.	[103]
North German Basin's current anticlinal configuration	Utilizes numerical simulation to assess the viability of UHS implementation	Eclipse 300	With five storage wells, UHS can typically maintain a continuous power production of 245 MW for a week	[104]

Table 9. *Cont.*

Storage Formation	Purpose	Software Approaches	Comments	Sources
Depleted gas reservoir and aquifer	Examines gas mixing and hydrodynamics during UHS	Mathematical and numerical modeling utilizing DuMuX	In aquifers, gravity override is more noticeable than in gas reservoirs. Compared to molecular diffusion, mechanical dispersions are more aggressive and intensify the gas mixing process.	[105]

A review of UHS modeling research reveals an uneven focus across key areas. Hydrodynamics dominates, emphasizing the need to understand subsurface hydrogen flow and distribution for safety and feasibility. In contrast, geochemical interactions, geomechanical effects, and microbial activities critical for storage integrity and hydrogen quality remain underexplored. Modeling tools like CMG software align with current priorities, whereas machine learning (ML) gains traction for enhancing model accuracy and efficiency. Tools such as PHREEQC underscore the importance of diverse methodologies in addressing UHS challenges.

8. Knowledge Gaps and Future Research

The current study on UHS has revealed the following concerns and challenges that need to be addressed in future studies: (a) Optimizing Hydrogen Storage Efficiency and Reducing Costs: Current studies lack standardized cost-effectiveness metrics and data on hydrogen recovery efficiency across geological formations. Further research is needed to understand the impact of cushion gases, cycling frequency, and injection/withdrawal rate. (b) Ensure Long-Term Storage Security and Stability: Research gaps in underground hydrogen storage, such as geomechanical effects, geochemical interactions, and real-time leakage detection, necessitate comprehensive improvement for long-term storage security and stability. (c) Impact Assessment of Hydrogen Injection on Subsurface and Surface Stability: Research is required to assess the long-term impacts of hydrogen injection on subsurface stability and surface conditions, including potential ground deformation and seismicity, to establish safe injection guidelines and regulatory frameworks for long-term monitoring and risk management of hydrogen storage projects. (d) Optimizing Cushion Gas Injection for Enhanced Hydrogen Recovery: The selection of cushion gas mixtures, injection strategies, and well placement should be optimized to maximize hydrogen recovery while minimizing contamination and reducing operational costs in hydrogen storage systems. (e) Evaluating the Methanation Potential in CO_2-Buffered Hydrogen Storage: The methanation potential in CO_2-buffered hydrogen storage systems is under-explored, with limited research on controlling methane production, optimizing hydrogen recovery, and managing risks. (f) Commercial-Scale Hydrogen Storage Facility Modeling: The development of advanced modeling techniques like Co-Flow and Co-FlowX for commercial hydrogen storage facility assessment, economic feasibility studies, and scalable designs is insufficiently researched. (g) Comprehensive Environmental Impact and Risk Assessment: Research gaps in hydrogen storage, including potential impacts on groundwater quality and ecosystems, and the need for comprehensive life cycle assessments, highlight the need for further investigation for safe, sustainable, and environmentally responsible practices. (h) Development of Digital and Smart Monitoring Systems: The application of AI and machine learning to optimize hydrogen storage systems, enabling early leak detection, real-time anomaly detection, and environmental impact assessments, are areas that need further research.

9. Conclusions

Underground hydrogen storage (UHS) in geological formations is a pivotal technology for achieving global energy security and supporting the transition to renewable energy systems. Hydrogen, with its high efficiency, environmental benefits, and sustainability, is poised to become a cornerstone of future energy systems. However, the deployment of UHS faces multifaceted challenges that require careful consideration.

Depleted gas reservoirs are a promising option for storage due to their pre-existing infrastructure, favorable economics, and extensive storage capacity. The cost advantage of aquifers and salt caverns arises from reduced site characterization requirements and the reuse of existing petrochemical facilities. However, challenges such as hydrogen's high mobility, geochemical reactivity with reservoir fluids and rock matrix, and potential issues with gas containment require further studies. In aquifers, higher costs are driven by extensive site characterization needs, whereas salt caverns, though efficient for cyclic injection and withdrawal, involve substantial upfront leaching and brine disposal costs. Key considerations for UHS include the thermophysical properties of hydrogen, such as density, viscosity, diffusivity, and solubility, which influence injectivity, withdrawal efficiency, and gas mobilization.

Similarly, petrophysical properties such as porosity and permeability directly affect the reservoir's storage capacity and containment integrity. The interplay of cushion gas requirements, depth, and geological viability further adds to the complexity of site selection, and operational planning expenditures (OPEX) are highly site-dependent and influenced by surface infrastructure, depth, and reservoir-specific factors. Hydrogen production costs, particularly those from electrolysis, remain a bottleneck, underscoring the importance of technological advancements to reduce expenses. Cushion gas strategies, material costs, and maintenance also play significant roles in shaping the financial outlook of UHS projects.

The realization of UHS at an industrial scale requires overcoming geological, economic, technological, and regulatory barriers. A phased approach combining experimental studies, simulation analyses, and demonstrated projects is essential to address safety concerns, improve gas containment, and optimize operational strategies. Geochemical interactions, well integrity, and potential microbial reactions with stored hydrogen must also be carefully managed to ensure long-term viability.

In conclusion, while UHS offers unparalleled potential for large-scale energy storage, its success hinges on continued research, innovation, and investment. Addressing current challenges through interdisciplinary efforts will pave the way for hydrogen to play a transformative role in achieving a low-carbon energy future.

Author Contributions: Conceptualization, K.O.D., W.A. and H.R.; methodology, K.O.D., H.R. and W.A.; validation, K.O.D., W.A., H.R. and M.M.; formal analysis, K.O.D., W.A. and H.R.; investigation, K.O.D., W.A. and H.R.; resources, W.A.; writing—original draft preparation, K.O.D., W.A. and H.R.; writing—review and editing, K.O.D., W.A., H.R. and M.M; visualization, K.O.D., W.A. and H.R.; supervision, W.A.; project administration, W.A.; funding acquisition, W.A. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the U.S. Department of Energy (DOE) through the National Energy Technology Laboratory to New Mexico Institute of Mining and Technology under award DE-FE0032363, the CUSP Regional Initiative project. Additional support was provided by the New Mexico Consortium (subcontract No. AP-045578) through the U.S. Department of Energy under Contract No. 89233218CNA000001.

Data Availability Statement: All data used in this study are obtained from previously published literature, which has been appropriately cited in the references section.

Acknowledgments: We thank the U.S. DOE for providing the funding support for this work and the Petroleum Recovery and Research Center, New Mexico Tech, for providing additional support and resources. We also thank the MDPI editorial team and anonymous reviewers for their helpful comments on this article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. World Bank. World Population Will Continue to Grow. World Development Indicators. Available online: https://datatopics.worldbank.org/world-development-indicators/stories/world-population-will-continue-to-grow.html (accessed on 19 October 2024).
2. Najjar, Y.S.H. Hydrogen Safety: The Road Toward Green Technology. *Int. J. Hydrogen Energy* **2013**, *38*, 10716–10728. [CrossRef]
3. BP. *Statistical Review of World Energy 2020*, 69th ed.; BP P.L.C.: London, UK, 2020. Available online: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf (accessed on 19 October 2024).
4. Zhou, J.; Ji, W.; Cao, X.; He, W.; Fan, J.; Yuan, Y. A Current Perspective on the Renewable Energy Hydrogen Production Process. *J. Therm. Sci.* **2023**, *32*, 542–596. [CrossRef]
5. Chandler, L. Making the Case for Hydrogen in a Zero-Carbon Economy. *MIT News*, 31 August 2021. Available online: https://news.mit.edu/2021/making-case-hydrogen-zero-carbon-economy-0831 (accessed on 19 October 2024).
6. IRENA. *Hydrogen: A Renewable Energy Perspective*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2019. Available online: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Hydrogen_2019.pdf (accessed on 19 October 2024).
7. OECD. Hydrogen Production. In *Technology Roadmap: Hydrogen and Fuel Cells*; OECD Publishing: Paris, France, 2015. Available online: https://www.oecd-ilibrary.org/docserver/093f609e-en.pdf (accessed on 19 October 2024).
8. Ziobrowski, Z.; Rotkegel, A. Assessment of Hydrogen Energy Industry Chain Based on Hydrogen Production Methods, Storage, and Utilization. *Energies* **2024**, *17*, 1808. [CrossRef]
9. Crotogino, F.; Donadei, S.; Bünger, U.; Landinger, H. Large-Scale Hydrogen Underground Storage for Securing Future Energy Supplies. In Proceedings of the 18th World Hydrogen Energy Conference (WHEC 2010), Essen, Germany, 16–21 May 2010; pp. 37–45.
10. Martin, J.; Burt, G.; Haszeldine, R.S.; Heinemann, N.; Kaemmer, N.; Rudloff, D.; Scafidi, J.; Shipton, Z.K. A review of challenges with using the natural gas system for hydrogen. *Energy Sci. Eng.* **2024**, *12*, 3995–4009. [CrossRef]
11. Clean Hydrogen Joint Undertaking. *The European Hydrogen Market Landscape*; Clean Hydrogen JU: Brussels, Belgium, 2024. Available online: https://observatory.clean-hydrogen.europa.eu/sites/default/files/2024-11/The%20European%20hydrogen%20market%20landscape_November%202024.pdf (accessed on 20 January 2025).
12. The Color Palette of the Colorless Hydrogen. Available online: https://jpt.spe.org/twa/the-color-palette-of-the-colorless-hydrogen (accessed on 20 January 2025).
13. Li, R.; Kawanami, H. A Recent Review of Primary Hydrogen Carriers, Hydrogen Production Methods, and Applications. *Catalysts* **2023**, *13*, 562. [CrossRef]
14. ATCO. Hydrogen Types. Available online: https://www.atco.com/content/dam/web/projects/projects-overview/hydrogen/hydrogen-types.pdf (accessed on 20 January 2025).
15. Jeje, S.O.; Marazani, T.; Obiko, J.O.; Shongwe, M.B. Advancing the Hydrogen Production Economy: A Comprehensive Review of Technologies, Sustainability, and Future Prospects. *Int. J. Hydrogen Energy* **2024**, *78*, 642–661. [CrossRef]
16. Ni, M.; Leung, D.Y.C.; Leung, M.K.H.; Sumathy, K. An Overview of Hydrogen Production from Biomass. *Fuel Process. Technol.* **2006**, *87*, 461–472. [CrossRef]
17. Hydrogen Council. *Interview: Hydrogen Spot Markets a Decade Away, but Costs Falling Fast*; S&P Global Commodity Insights: London, UK, 2021. Available online: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/041221-interview-hydrogen-spot-markets-a-decade-away-but-costs-falling-fast-hydrogen-council (accessed on 19 October 2024).
18. World Nuclear Association. Hydrogen Production and Uses. Available online: https://world-nuclear.org/information-library/energy-and-the-environment/hydrogen-production-and-uses (accessed on 20 January 2025).
19. Department of Mineral Resources and Energy. Consultation Document on the Development of a Gas, Renewables and Hydrogen Partnership Strategy in SA; Republic of South Africa, February 2023. Available online: https://cer.org.za/wp-content/uploads/2023/02/Consultation-document-on-the-developmnet-of-a-gas-renewables-and-hydrogen-partnership-strategy-in-SA.pdf (accessed on 20 January 2025).

20. Taiwo, G.O.; Tomomewo, O.S.; Oni, B.A. A Comprehensive Review of Underground Hydrogen Storage: Insight into Geological Sites (Mechanisms), Economics, Barriers, and Future Outlook. *J. Energy Storage* **2024**, *90 Pt B*, 111844. [CrossRef]
21. Navaid, H.B.; Emadi, H.; Watson, M. A Comprehensive Literature Review on the Challenges Associated with Underground Hydrogen Storage. *J. Nat. Gas Sci. Eng.* **2023**, *109*, 104952. [CrossRef]
22. Okoroafor, E.R.; Saltzer, S.D.; Kovscek, A.R. Toward Underground Hydrogen Storage in Porous Media: Reservoir Engineering Insights. *Int. J. Hydrogen Energy* **2022**, *47*, 33781–33802. [CrossRef]
23. Duartey, K.O.; Quainoo, A.K.; Darko, C.K. Evaluation Studies of KCl and Amino Acid Mixtures for Clay Stabilization and Rheological Enhancement of Water-Based Fracturing Fluids. In Proceedings of the SPE Nigeria Annual International Conference and Exhibition, Lagos, Nigeria, 5–7 August 2024.
24. Fuentes, J.E.Q.; Santos, D.M.F. Technical and Economic Viability of Underground Hydrogen Storage. *Hydrogen* **2023**, *4*, 975–1000. [CrossRef]
25. IDTechEx. Hydrogen Economy 2023-2033: Production, Storage, Distribution & Applications. Available online: https://www.idtechex.com/en/research-report/hydrogen-economy-2023-2033-production-storage-distribution-and-applications/908 (accessed on 20 January 2025).
26. Bade, S.O.; Taiwo, K.; Ndulue, U.F.; Tomomewo, O.S.; Oni, B.A. A Review of Underground Hydrogen Storage Systems: Current Status, Modeling Approaches, Challenges, and Future Prospective. *Int. J. Hydrogen Energy* **2024**, *80*, 449–474. [CrossRef]
27. Shazad, A.; Uzair, M.; Tufail, M. Impact of Blending of Phase Change Material for Performance Enhancement of Solar Energy Storage. *Renew. Energy* **2024**, *227*, 120530. [CrossRef]
28. Hydrogen Council; McKinsey & Company. Hydrogen Insights 2024. May 2024. Available online: https://hydrogencouncil.com/wp-content/uploads/2023/05/Hydrogen-Insights-2023.pdf (accessed on 19 October 2024).
29. Jahanbakhsh, A.; Potapov-Crighton, A.L.; Mosallanezhad, A.; Tohidi Kaloorazi, N.; Maroto-Valer, M.M. Underground Hydrogen Storage: A UK Perspective. *Renew. Sustain. Energy Rev.* **2024**, *189*, 114001. [CrossRef]
30. The Effects of Hydrogen Injection in Natural Gas Networks for the Dutch Underground Storages. 2017. Available online: https://www.scribd.com/document/507760964/The-Effects-of-Hydrogen-Injection-in-Natural-Gas-Networks-for-the-Dutch-Underground-Storages (accessed on 15 August 2023).
31. Sambo, C.; Dudun, A.; Samuel, S.A.; Esenenjor, P.; Muhammed, N.S.; Haq, B. A Review on Worldwide Underground Hydrogen Storage Operating and Potential Fields. *Int. J. Hydrogen Energy* **2022**, *47*, 22840–22880. [CrossRef]
32. Zivar, D.; Kumar, S.; Foroozesh, J. Underground Hydrogen Storage: A Comprehensive Review. *Int. J. Hydrogen Energy* **2021**, *46*, 23436–23462. [CrossRef]
33. Statista. Forecast Hydrogen Storage Capacity Worldwide | Statista. Available online: https://www.statista.com/statistics/1500329/hydrogen-storage-capacity-forecast-global/ (accessed on 29 October 2024).
34. HyStock. Large-Scale Underground Hydrogen Storage. Available online: https://www.hystock.nl/en (accessed on 20 January 2025).
35. HyPSTER. Press Release November 2024—HyPSTER. Available online: https://hypster-project.eu/press-release-november-2024/ (accessed on 20 January 2025).
36. Sandia National Laboratories. Sandia Studies Subterranean Storage of Hydrogen. Available online: https://www.sandia.gov/labnews/2024/04/04/sandia-studies-subterranean-storage-of-hydrogen/ (accessed on 20 January 2025).
37. Vallourec. Vallourec Revolutionizes Hydrogen Storage with Delphy, Its Large-Scale Vertical Solution. Available online: https://www.vallourec.com/news/vallourec-revolutionizes-hydrogen-storage-with-delphy-its-large-scale-vertical-solution/ (accessed on 20 January 2025).
38. Global Hydrogen Review. HyStorage First Test Phase Successful. Available online: https://www.globalhydrogenreview.com/hydrogen/13032024/hystorage-first-test-phase-successful/ (accessed on 20 January 2025).
39. ACES Delta. ACES Delta: Advanced Clean Energy Storage Site. Available online: https://aces-delta.com (accessed on 20 January 2025).
40. U.S. Department of Energy (DOE). DOE Three-Year U.S. Underground Hydrogen Storage Assessment. Available online: https://www.energy.gov/fecm/articles/doe-three-year-us-underground-hydrogen-storage-assessment-expands-future (accessed on 20 January 2025).
41. EUH2STARS. European Underground Hydrogen Storage Reference System. Available online: https://www.euh2stars.eu/en/publications/press-information/details/article/euh2stars-european-underground-hydrogen-storage-reference-system.html (accessed on 20 January 2025).
42. Clean Hydrogen Partnership—European Union. HyUnder—Hydrogen Underground Storage. Available online: https://www.clean-hydrogen.europa.eu/projects-dashboard/projects-repository/hyunder_en (accessed on 20 January 2025).
43. Hystories. Hydrogen Storage in European Subsurface. Available online: https://hystories.eu (accessed on 20 January 2025).
44. H2eart for Europe. Hydrogen Underground Storage Roadmap. Available online: https://h2eart.eu (accessed on 20 January 2025).

45. Muhammed, N.S.; Haq, B.; Al Shehri, D.; Al-Ahmed, A.; Rahman, M.M.; Zaman, E. A Review on Underground Hydrogen Storage: Insight into Geological Sites, Influencing Factors and Future Outlook. *Energy Rep.* **2022**, *8*, 461–499. [CrossRef]
46. Gholami, R. Hydrogen Storage in Geological Porous Media: Solubility, Mineral Trapping, H_2S Generation and Salt Precipitation. *Int. J. Hydrogen Energy* **2022**, *47*, 18850–18865. [CrossRef]
47. Heinemann, N.; Alcalde, J.; Miocic, J.M.; Hangx, S.J.; Kallmeyer, J.; Ostertag-Henning, C.; Hassanpouryouzband, A.; Thaysen, E.M.; Strobel, G.J.; Schmidt-Hattenberger, C.; et al. Enabling Large-Scale Hydrogen Storage in Porous Media—The Scientific Challenges. *Energy Environ. Sci.* **2021**, *14*, 853–864. [CrossRef]
48. Ebrahimiyekta, A. Characterization of Geochemical Interactions and Migration of Hydrogen in Sandstone Sedimentary Formations: Application to Geological Storage. Ph.D. Dissertation, Université d'Orléans, Orléans, France, 2017. Available online: https://theses.hal.science/tel-01713106v1/file/alireza-ebrahimiyekta_3466.pdf (accessed on 19 October 2024).
49. Hematpur, H.; Abdollahi, R.; Rostami, S.; Haghighi, M. Review of Underground Hydrogen Storage: Concepts and Challenges. *Adv. Geo-Energy Res.* **2022**, *7*, 111–131. [CrossRef]
50. Davoodabadi, A.; Mahmoudi, A.; Ghasemi, H. The Potential of Hydrogen Hydrate as a Future Hydrogen Storage Medium. *iScience* **2020**, *24*, 101907. [CrossRef]
51. Ghazi, M.R.; Schicks, J.M.; English, N.J. A Review of Reactor Designs for Hydrogen Storage in Clathrate Hydrates. *Appl. Sci.* **2021**, *11*, 469. [CrossRef]
52. Delshad, M.; Tavakoli, R.; Sepehrnoori, K. Advances in Hydrogen Storage in Porous Media: A Review of Geological and Engineering Aspects. *Int. J. Hydrogen Energy* **2022**, *47*, 2309–2330. [CrossRef]
53. Katz, D.L.; Tek, M.R. Storage of Natural Gas in Saline Aquifers. *Water Resour. Res.* **1970**, *6*, 1515–1521. [CrossRef]
54. Uliasz-Misiak, B.; Misiak, J. Underground Gas Storage in Saline Aquifers: Geological Aspects. *Energies* **2024**, *17*, 1666. [CrossRef]
55. Saeed, M.; Jadhawar, P. Modelling Underground Hydrogen Storage: A State-of-the-Art Review of Fundamental Approaches and Findings. *Gas Sci. Eng.* **2024**, *121*, 205196. [CrossRef]
56. Braid, H.; Taylor, K.; Hough, E.; Rochelle, C.; Niasar, V.; Ma, L. Hydrogen-induced mineral alteration: A review in the context of underground hydrogen storage (UHS) in saline aquifers. *Earth-Sci. Rev.* **2024**, *259*, 104975. [CrossRef]
57. Hemme, C.; Van Berk, W. Hydrogeochemical Modeling to Identify Potential Risks of Underground Hydrogen Storage in Depleted Gas Fields. *Appl. Sci.* **2018**, *8*, 2282. [CrossRef]
58. Flesch, S.; Pudlo, D.; Albrecht, D.; Jacob, A.; Enzmann, F. Hydrogen Underground Storage—Petrographic and Petrophysical Variations in Reservoir Sandstones from Laboratory Experiments under Simulated Reservoir Conditions. *Int. J. Hydrogen Energy* **2018**, *43*, 20822–20835. [CrossRef]
59. Hassanpouryouzband, A.; Adie, K.; Cowen, T.; Thaysen, E.M.; Heinemann, N.; Butler, I.B.; Wilkinson, M.; Edlmann, K. Geological Hydrogen Storage: Geochemical Reactivity of Hydrogen with Sandstone Reservoirs. *ACS Energy Lett.* **2022**, *7*, 2405–2410. [CrossRef] [PubMed]
60. Hemme, C. Storage of Gases in Deep Geological Structures: Spatial and Temporal Hydrogeochemical Processes Evaluated and Predicted by the Development and Application of Numerical Modeling. Ph.D. Thesis, Clausthal University of Technology, Clausthal-Zellerfeld, Germany, 2019. [CrossRef]
61. Hassannayebi, N.; Azizmohammadi, S.; De Lucia, M.; Ott, H. Underground Hydrogen Storage: Application of Geochemical Modelling in a Case Study in the Molasse Basin, Upper Austria. *Environ. Earth Sci.* **2019**, *78*, 177. [CrossRef]
62. Sun, B.; Zhang, M.; Sun, Q.; Zhong, J.; Shao, G. Review on natural hydrogen wells safety. *Nat. Commun.* **2025**, *16*, 369. [CrossRef] [PubMed]
63. Hemme, C.; van Berk, W. Change in Cap Rock Porosity Triggered by Pressure and Temperature Dependent CO_2–Water–Rock Interactions in CO_2 Storage Systems. *Petroleum* **2017**, *3*, 96–108. [CrossRef]
64. Zhu, C. In Situ Feldspar Dissolution Rates in an Aquifer. *Geochim. Cosmochim. Acta* **2005**, *69*, 1435–1453. [CrossRef]
65. Gomez Mendez, I.; El-Sayed, W.M.M.; Menefee, A.H.; Karpyn, Z.T. Insights into Underground Hydrogen Storage Challenges: A Review on Hydrodynamic and Biogeochemical Experiments in Porous Media. *Energy Fuels* **2024**, *38*, 12345–12360. [CrossRef]
66. Dopffel, N.; Jansen, S.; Gerritse, J. Microbial Side Effects of Underground Hydrogen Storage—Knowledge Gaps, Risks and Opportunities for Successful Implementation. *Int. J. Hydrogen Energy* **2021**, *46*, 8594–8606. [CrossRef]
67. Rivolta, G.; Maniglio, M.; Elgendy, A.; Panfili, P.; Cominelli, A. Evaluating the Impact of Biochemical Reactions on H2 Storage in Depleted Gas Fields. *SPE J.* **2024**, *29*, 4494–4509. [CrossRef]
68. Zeng, L.; Sarmadivaleh, M.; Saeedi, A.; Chen, Y.; Zhong, Z.; Xie, Q. Storage Integrity During Underground Hydrogen Storage in Depleted Gas Reservoirs. *Earth-Sci. Rev.* **2023**, *247*, 104625. [CrossRef]
69. Malki, M.L.; Chellal, H.; Mao, S.; Rasouli, V.; Mehana, M. A Critical Review of Underground Hydrogen Storage: From Fundamentals to Applications, Unveiling Future Frontiers in Energy Storage. *Int. J. Hydrogen Energy* **2024**, *79*, 1365–1394. [CrossRef]
70. Boon, M.; Buntic, I.; Ahmed, K.; Dopffel, N.; Peters, C.; Hajibeygi, H. Microbial Induced Wettability Alteration with Implications for Underground Hydrogen Storage. *Sci. Rep.* **2024**, *14*, 8248. [CrossRef] [PubMed]

71. Adam, A.M.; Bahamon, D.; Al Kobaisi, M.; Vega, L.F. Molecular Dynamics Simulations of the Interfacial Tension and the Solubility of Brine/H_2/CO_2 Systems: Implications for Underground Hydrogen Storage. *Int. J. Hydrogen Energy* **2024**, *78*, 1344–1354. [CrossRef]
72. Aslannezhad, M.; Ali, M.; Kalantariasl, A.; Sayyafzadeh, M.; You, Z.; Iglauer, S.; Keshavarz, A. A Review of Hydrogen/Rock/Brine Interaction: Implications for Hydrogen Geo-storage. *Prog. Energy Combust. Sci.* **2023**, *95*, 101066. [CrossRef]
73. Peters, E.J. Dispersion in Porous Media. In *Advanced Petrophysics: Dispersion, Interfacial Phenomena/Wettability, Capillarity/Capillary Pressure, Relative Permeability*; Live Oak Book Company: Gaithersburg, MD, USA, 2012; Volume 2.
74. Rezaei, A.; Hassanpouryouzband, A.; Molnar, I.; Derikvand, Z.; Haszeldine, R.S.; Edlmann, K. Relative Permeability of Hydrogen and Aqueous Brines in Sandstones and Carbonates at Reservoir Conditions. *Geophys. Res. Lett.* **2022**, *49*, e2022GL099433. [CrossRef]
75. Mirchi, V.; Dejam, M.; Alvarado, V. Interfacial Tension and Contact Angle Measurements for Hydrogen-Methane Mixtures/Brine/Oil-Wet Rocks at Reservoir Conditions. *Int. J. Hydrogen Energy* **2022**, *47*, 34963–34975. [CrossRef]
76. Thaysen, E.M.; Butler, I.B.; Hassanpouryouzband, A.; Freitas, D.; Alvarez-Borges, F.; Krevor, S.; Heinemann, N.; Atwood, R.; Edlmann, K. Pore-Scale Imaging of Hydrogen Displacement and Trapping in Porous Media. *Int. J. Hydrogen Energy* **2023**, *48*, 3091–3103. [CrossRef]
77. Boon, M.; Hajibeygi, H. Experimental Characterization of H_2/Water Multiphase Flow in Heterogeneous Sandstone Rock at the Core Scale Relevant for Underground Hydrogen Storage (UHS). *Sci. Rep.* **2022**, *12*, 14604. [CrossRef] [PubMed]
78. Carden, P.O.; Paterson, L. Physical, Chemical and Energy Aspects of Underground Hydrogen Storage. *Int. J. Hydrogen Energy* **1979**, *4*, 559–569. [CrossRef]
79. Jangda, Z.; Menke, H.; Busch, A.; Geiger, S.; Bultreys, T.; Lewis, H.; Singh, K. Pore-Scale Visualization of Hydrogen Storage in a Sandstone at Subsurface Pressure and Temperature Conditions: Trapping, Dissolution and Wettability. *J. Colloid Interface Sci.* **2023**, *629 Pt B*, 316–325. [CrossRef]
80. Lysyy, M.; Ersland, G. Pore-Scale Dynamics for Underground Porous Media Hydrogen Storage. *Adv. Water Resour.* **2022**, *163*, 104167. [CrossRef]
81. Amiri, I.I.; Zivar, D.; Ayatollahi, S.; Mahani, H. The Effect of Gas Solubility on the Selection of Cushion Gas for Underground Hydrogen Storage in Aquifers. *J. Energy Storage* **2024**, *80*, 110264. [CrossRef]
82. Shi, Z.; Driba, D.L.; Lopez Rivera, N.; Kariminasab, M.; Beckingham, L.E. A Review of Coupled Geochemical–Geomechanical Impacts in Subsurface CO_2, H_2, and Air Storage Systems. *Energies* **2024**, *17*, 2928. [CrossRef]
83. Kumar, K.R.; Honorio, H.; Chandra, D.; Lesueur, M.; Hajibeygi, H. Comprehensive Review of Geomechanics of Underground Hydrogen Storage in Depleted Reservoirs and Salt Caverns. *J. Energy Storage* **2023**, *73*, 108912. [CrossRef]
84. Zeng, L.; Vialle, S.; Ennis-King, J.; Esteban, L. Role of Geochemical Reactions on Caprock Integrity During Underground Hydrogen Storage. *J. Energy Storage* **2022**, *65*, 107414. [CrossRef]
85. Laban, M. Hydrogen Storage in Salt Caverns: Chemical Modelling and Analysis of Large-Scale Hydrogen Storage in Underground Salt Caverns. June 2020. Available online: https://www.researchgate.net/publication/371044665_Hydrogen_storage_in_salt_caverns_Chemical_modelling_and_analysis_of_large-scale_hydrogen_storage_in_underground_salt_caverns (accessed on 20 January 2025).
86. Alms, K.; Berndsen, M.; Groeneweg, A.; Graf, M.; Nehler, M.; Ahrens, B. Underground Hydrogen Storage in the Bunter Sandstone Formation in the North German Basin: Capacity Assessment and Geochemical Modeling. *Energy Technol.* **2023**, *11*, 2300847. [CrossRef]
87. Blyton, C.A.J.; Gala, D.P.; Sharma, M.M. A Comprehensive Study of Proppant Transport in a Hydraulic Fracture. In Proceedings of the SPE Annual Technical Conference and Exhibition, Houston, TX, USA, 28–30 September 2015; pp. 3391–3411. [CrossRef]
88. Böttcher, N.; Görke, U.-J.; Kolditz, O.; Nagel, T. Thermo-Mechanical Investigation of Salt Caverns for Short-Term Hydrogen Storage. *Environ. Earth Sci.* **2017**, *76*, 98. [CrossRef]
89. Kumar, K.R.; Makhmutov, A.; Spiers, C.J.; Hajibeygi, H. Geomechanical Simulation of Energy Storage in Salt Formations. *Sci. Rep.* **2021**, *11*, 19640. [CrossRef]
90. Fang, Y.; Hou, Z.; Yue, Y.; Chen, Q.; Liu, J. Numerical Study of Hydrogen Storage Cavern in Thin-Bedded Rock Salt, Anning of China. In *The Mechanical Behavior of Salt X*, 1st ed.; Fahland, S., Lux, K.H., Minkley, W., Stahlmann, J., Eds.; CRC Press: London, UK, 2022; pp. 652–661. [CrossRef]
91. Coarita-Tintaya, E.-D.; Golfier, F.; Grgic, D.; Souley, M.; Cheng, L. Hydromechanical Modelling of Salt Caverns Subjected to Cyclic Hydrogen Injection and Withdrawal. *Comput. Geotech.* **2023**, *162*, 105690. [CrossRef]
92. Bai, T.; Tahmasebi, P. Coupled Hydro-Mechanical Analysis of Seasonal Underground Hydrogen Storage in a Saline Aquifer. *J. Energy Storage* **2022**, *50*, 104308. [CrossRef]
93. Gbadamosi, A.O.; Muhammed, N.; Patil, S.; Al Shehri, D.; Haq, B.; Epelle, E.I.; Mahmoud, M.; Kamal, M.S. Underground hydrogen storage: A critical assessment of fluid-fluid and fluid-rock interactions. *J. Energy Storage* **2023**, *71*, 108155. [CrossRef]

94. Koch, T.; Gläser, D.; Weishaupt, K.; Ackermann, S.; Beck, M.; Becker, B.; Burbulla, S.; Class, H.; Coltman, E.; Emmert, S.; et al. DuMux 3—An Open-Source Simulator for Solving Flow and Transport Problems in Porous Media with a Focus on Model Coupling. *Comput. Math. Appl.* **2021**, *81*, 423–443. [CrossRef]
95. Dickinson, E.J.F.; Ekström, H.; Fontes, E. COMSOL Multiphysics®: Finite Element Software for Electrochemical Analysis. A Mini-Review. *Electrochem. Commun.* **2014**, *40*, 71–74. [CrossRef]
96. Pruess, K.; Oldenburg, C.M.; Moridis, G.J. *TOUGH2 User's Guide Version 2*; U.S. Department of Energy: Washington, DC, USA, 1999. [CrossRef]
97. Computer Modelling Group. *CMG User Manual*; Computer Modelling Group: Calgary, AB, Canada, 2022. Available online: https://www.cmgl.ca/resources/ (accessed on 20 January 2025).
98. Kanaani, M.; Sedaee, B.; Asadian-Pakfar, M. Role of Cushion Gas on Underground Hydrogen Storage in Depleted Oil Reservoirs. *J. Energy Storage* **2022**, *45*, 103783. [CrossRef]
99. Abdellatif, M.; Hashemi, M.; Azizmohammadi, S. Large-Scale Underground Hydrogen Storage: Integrated Modeling of Reservoir-Wellbore System. *Int. J. Hydrogen Energy* **2023**, *48*, 19160–19171. [CrossRef]
100. Luboń, K.; Tarkowski, R. The Influence of the First Filling Period Length and Reservoir Level Depth on the Operation of Underground Hydrogen Storage in a Deep Aquifer. *Int. J. Hydrogen Energy* **2023**, *48*, 1024–1042. [CrossRef]
101. Hagemann, B.; Rasoulzadeh, M.; Panfilov, M.; Ganzer, L.; Reitenbach, V. Hydrogenization of Underground Storage of Natural Gas. *Comput. Geosci.* **2016**, *20*, 595–606. [CrossRef]
102. Anderson, J.; Grönkvist, S. A Comparison of Two Hydrogen Storages in a Fossil-Free Direct Reduced Iron Process. *Int. J. Hydrogen Energy* **2021**, *46*, 28657–28674. [CrossRef]
103. Wang, G.; Pickup, G.; Sorbie, K.; Mackay, E. Scaling Analysis of Hydrogen Flow with Carbon Dioxide Cushion Gas in Sub-Surface Heterogeneous Porous Media. *Int. J. Hydrogen Energy* **2022**, *47*, 1752–1764. [CrossRef]
104. Pfeiffer, W.T.; Beyer, C.; Bauer, S. Hydrogen Storage in a Heterogeneous Sandstone Formation: Dimensioning and Induced Hydraulic Effects. *Pet. Geosci.* **2017**, *23*, 315–326. [CrossRef]
105. Feldmann, F.; Hagemann, B.; Ganzer, L.; Panfilov, M. Numerical Simulation of Hydrodynamic and Gas Mixing Processes in Underground Hydrogen Storages. *Environ. Earth Sci.* **2016**, *75*, 1165. [CrossRef]