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Review

Technical and Economic Viability of Underground Hydrogen Storage

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Abstract: Considering the mismatch between the renewable source availability and energy demand, energy storage is increasingly vital for achieving a net-zero future. The daily/seasonal disparities produce a surplus of energy at specific moments. The question is how can this "excess" energy be stored? One promising solution is hydrogen. Conventional hydrogen storage relies on manufactured vessels. However, scaling the technology requires larger volumes to satisfy peak demands, enhance the reliability of renewable energies, and increase hydrogen reserves for future technology and infrastructure development. The optimal solution may involve leveraging the large volumes of underground reservoirs, like salt caverns and aquifers, while minimizing the surface area usage and avoiding the manufacturing and safety issues inherent to traditional methods. There is a clear literature gap regarding the critical aspects of underground hydrogen storage (UHS) technology. Thus, a comprehensive review of the latest developments is needed to identify these gaps and guide further R&D on the topic. This work provides a better understanding of the current situation of UHS and its future challenges. It reviews the literature published on UHS, evaluates the progress in the last decades, and discusses ongoing and carried-out projects, suggesting that the technology is technically and economically ready for today's needs.

Keywords: green hydrogen; underground hydrogen storage; geological structures; salt caverns; aquifers

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1. Introduction

The past decades have seen an increase in the share of renewable energy sources in the energy mix, showing the importance of decarbonizing the energy sector. However, their intermittent nature poses a challenge when aiming for a successful transition. While mechanical storage technologies like pumped hydro and compressed-air energy storage have the potential to mitigate the fluctuations in renewable energy sources, the limited storage density of water and compressed air hinders their large-scale implementation, particularly for long-term seasonal storage. It has become generally accepted that the surplus of renewable energy should be used to power water electrolyzers and produce green hydrogen, which fits into the well-known Power-to-X technologies.

Besides its numerous uses, such as propelling fuel, feedstock for fertilizer industry and oil refining, hydrogen is recognized as a secondary source of energy, and an essential energy carrier [1]. In contrast to mechanical energy storage, chemical energy carriers (like hydrogen or natural gas) offer an energy density approximately 100 times higher than compressed-air energy storage for the same storage volume. The combustion of 1 m^3 of hydrogen produces 12.7 MJ of energy, although it is three times lower than that from methane combustion (40 MJ). Hydrogen is not considered an energy source because the energy needed to create it is more than the one it produces when consumed. However, converting it to heat or electricity is easy, as it is an efficient energy carrier because of its transporting and storing capabilities. As an example, the loss during energy transportation by a gaseous carrier (<0.1%) is much lower than that using the power network (8%) [1]. Thus, hydrogen storage is directly related to energy storage.

It should be emphasized that not all hydrogen is green. In fact, hydrogen can be produced through different processes, including thermochemical, electrochemical, and biological processes, or direct solar water splitting. Most of the current production comes from fossil fuels (grey, black, and brown hydrogen). With the expected increase in green hydrogen production, efficient storage methods will be required, and underground hydrogen storage (UHS) systems might present a crucial solution. It is important to acknowledge how large the storage capacity needs to be (hydrogen has a lower energy density when compared to methane). Underground formations, including depleted gas fields, aquifers, and salt caverns, can satisfy such volumes. Pipelines or vessels can also be considered viable options. Still, underground salt caverns are more favorable for seasonal storage than above-ground storage technologies [2]. Other storage options, such as abandoned coal mines, lined hard rock caverns, and refrigerated mined caverns, are expected to become more popular as the demand for storage grows, especially in regions where depleted reservoirs, aquifers, and salt deposits are not available [1].

Besides satisfying the storage capacity, the structures mentioned present a safer environment than above-ground options mainly because of the absence of atmospheric oxygen; the mixture of hydrogen and this gas is unstable even in small concentrations. In addition, large storage volumes make operations economically viable and enable an economic threshold.

Figure 1 shows, at a generic location, how the surplus energy that renewable sources have above ground could be used to produce hydrogen and store it underground (the general idea of UHS). It also reflects an essential aspect of the technology: the depths at which the storage structures are usually found. The depleted hydrocarbon reservoirs (mainly depleted gas fields) are the type of structures that are the deepest on the earth's crust. This involves challenging drilling, although most of the infrastructure used in the past to operate the reservoirs can be reused. Closer to the surface, there are formations like aquifers and salt caverns. Their specific depths will influence their storage capacities. Finally, the structures closer to the surface are rock caverns, which are still behind in the UHS race, as the cost of storage per kilogram of hydrogen is more than double when compared to the other three formations mentioned [1], mainly due to the lack of a natural impermeable layer (or seal).

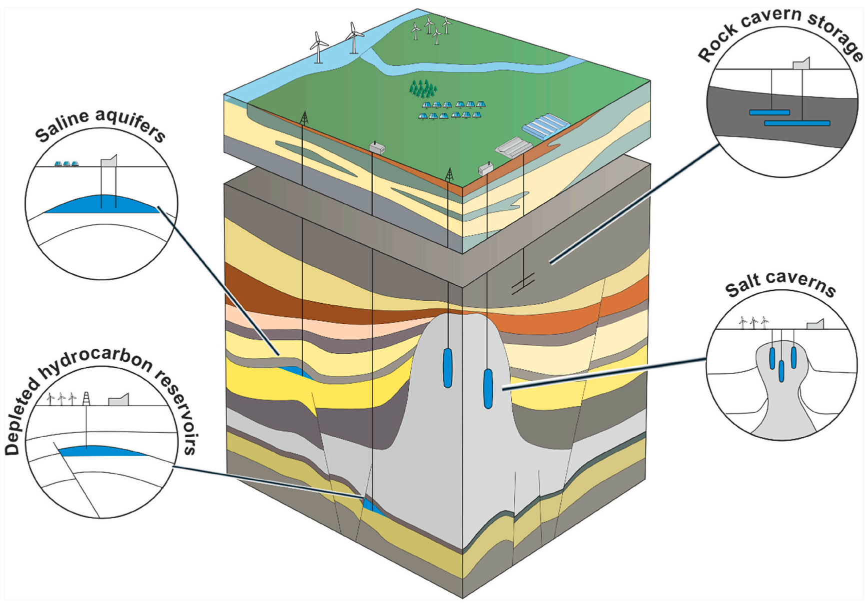

Figure 1. Geological structures suitable for underground hydrogen storage (UHS) [3].

The performance of these geological structures for UHS is largely determined by hydrogen's physical properties. Taking methane (natural gas) as a reference, as the underground storage of this gas has been widely studied and practiced, the first difference to stand out is the density difference, with methane being eight times denser than hydrogen (see Table 1), a point that raises the role of the storage capacity.

Table 1. Physical properties of hydrogen and methane. Adapted from [1] with permission from Elsevier.

Properties	H_2	CH_4
Molecular weight	2.016	16.043
Density (25 °C, 1 atm)	0.082 kg/m^3	0.657 kg/m^3
Viscosity (25 °C, 1 atm)	0.89×10^{-5} Pa s	1.1×10^{-5} Pa s
Solubility in pure water (20 °C, 1 atm)	0.0016 g_{H2}/kg_{H2O}	0.023 g_{CH4}/kg_{H2O}
Boiling point	−253 °C	−165 °C
Critical pressure	12.8 atm	45.8 atm
Critical temperature	−240 °C	−82.3 °C
Heating value	120–142 kJ/g	205–55.5 kJ/g
Diffusion in pure water (25 °C)	5.13×10^{-9} m^2/s	1.85×10^{-9} m^2/s

Hydrogen is also less viscous; this translates into higher mobility, which, in porous media, could result in higher withdrawal efficiencies during the reservoir's loading and discharging cycles, avoiding potential fluid-coning issues. The lower solubility of hydrogen is seen as an advantage, especially when stored in saline aquifers or depleted gas and oil reservoirs, because lower losses due to dissolution are expected. This feature can be extrapolated to water–hydrogen–salt systems as typical storage systems.

A drawback is the low molecular weight of hydrogen, the lightest among all the elements, which means that leakage to the surface is likely to happen. In addition, the influence of porosity media makes a more suitable scenario for leakage.

Despite the importance of UHS for the success of the foreseen hydrogen economy, it should be emphasized that there is a literature gap regarding UHS, encompassing key aspects of the technology. This includes innovation in storage techniques, integration with renewable energies, safety and environmental concerns, economic feasibility and cost effectiveness, life cycle assessment, specific geopolitical challenges, ensuring hydrogen purity and quality during injection and withdrawal, and developing effective regulatory and policy frameworks. The present review systematically identifies these literature gaps, which is essential for guiding further research and development in the field of UHS.

2. Geological Structures for Underground Hydrogen Storage and Relevant Parameters

The concept of underground hydrogen storage (UHS) is less known than its natural gas counterpart, which is expected due to its less significant role in the past. Despite this, the insights gained with natural gas can be applied to hydrogen storage due to the shared cavern design and operation [2]. Thus, the current challenge for UHS technology developers is to address the differences, particularly in materials, access wells, cavern heads, and transmission infrastructure. Natural gas storage in an underground formation was first achieved in 1915 in a partially depleted gas field in Ontario, Canada. Since then, much experience has been gained in almost every aspect that UHS englobes, such as site specifications, storage techniques, monitoring, life cycle costs, and economic viability.

Geological sites suitable for the underground storage of gases can be classified into two main categories: (a) porous media, in which hydrogen is stored within the pore space of sandstones or carbonate formations, and (b) cavern storage, in which hydrogen is contained within excavated or solution-mined cavities in dense rock formations. The properties of the gas to be stored play a crucial role in the success of the storage operations. Each geological formation presents unique challenges, requiring an understanding of the specific parameters for each type.

2.1. Depleted Oil and Gas Reservoirs

Hydrocarbon reservoirs are typically porous and permeable rock formations like sandstones or carbonates. The hydrocarbons are trapped within the reservoir by impermeable rocks or seals, forming a subsurface reservoir that can be exploited through drilling and production techniques. After this, the structure remains empty and can be used for UHS. According to Kanaani et al. [4], depleted hydrocarbon reservoirs present the best choice for large-scale UHS thanks to their known geological structure, the proper compactness and integrity of the source rock, and the pre-existence of surface facilities. Furthermore, the tightness of the caprocks of depleted gas reservoirs has also been proven. However, transforming the depleted reservoir into a UHS site requires comprehensive studies. For example, the remaining gas on gas fields is advantageous because it can act as cushion gas. Conversely, it can be a disadvantage if this remaining gas reduces the hydrogen purity. In the case of residual oil, the chances of chemical reactions increase, and hydrogen may turn into (for example) methane.

Actual underground gas storage operations have proven that the storage process needs cushion gas (or base gas). N_2, CH_4, or CO_2, among others, can work as cushion gases. This requirement comes from the need to maintain the reservoir pressure, as hydrogen is being withdrawn. This gas is also important because it accompanies the hydrogen being produced, consequently affecting the quality of the hydrogen outflow. This highlights the urge to implement several purification steps for the hydrogen retrieval process, which are costly [4].

Ultimately, the main advantage of depleted reservoirs is the economic threshold that previous studies and site exploration present regarding the lifespan of such assets. UHS brings back the possibility of deep and ultra-deep oil and gas well drilling, as the well will generate profits from the oil and/or gas production and, later, from the UHS once the reservoir reaches its oil or gas production lifespan. This theoretical "second life" of the reservoir would begin after the point marked as abandonment in Figure 2, stretching the economic limit, which must be considered in the project's initial investment.

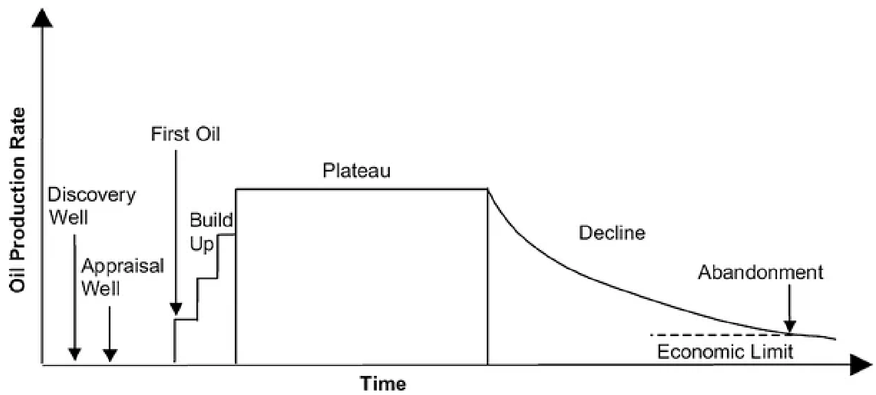

Figure 2. Conventional production profile of an oil field. Reprinted from [5] with permission from Springer Nature.

2.2. Aquifers

These formations are porous and permeable media full of pore spaces filled with fresh or saline water. Aquifers are distributed worldwide, which makes them a logical choice for UHS. Several reported cases in the literature on the use of aquifers for gas storage demonstrate their potential for hosting hydrogen. They accumulate the majority of the total natural gas storage in the subsurface. However, to date, no pure hydrogen storage has been reported. Gas storage with a composition of around 50% H_2 and 50% CH_4 has been reported in France, Germany, and the Czech Republic [1,6].

As mentioned, porous media use the pore space to store gas, but this does not imply that all porous media are suitable for UHS. Suitable aquifers may have a geology similar to depleted gas reservoirs [7]. Another condition preferable (if not necessary), that not all aquifers count with, is having an impermeable layer to inhibit the migration of the stored gas. This condition is accomplished via hydrocarbon reservoirs, as they are found deeper in the earth's crust. However, aquifers may not have been formed under the same critical conditions; consequently, some lack this characteristic. A downside related to this is the often more expensive development when compared to depleted reservoirs due to the uncertain geology and lack of infrastructure. Geologic characteristics are not well known, and data must be acquired to determine whether the formation can trap and seal the gas.

Other expenses in the construction of these UHS sites, besides exploration wells, include the construction of above-ground facilities, injection and extraction wells and circuits, and a system to dehydrate the hydrogen, given the presence of water in the structure. Not everything is disadvantageous with these formations; they present several positive points. The ease of finding them pretty much everywhere and the increased pressure due to the difference in density between the liquid and gas phases are the main benefits that make them an attractive option. Regarding this last characteristic, the overpressure of porous media could make up for faster hydrogen flow rates, higher recovery ratios, and, hence, fewer losses at the expense of a larger investment. Finding the proper site with a large storage volume could compensate for the additional costs for exploration and dehydration systems due to the higher operational efficiency.

Still, aquifers have a long way to go, with many abiotic and mineral reactions to consider in each project. Shallow extraction could minimize this, but the impermeable layer must exist to avoid the losses. Aquifers are a developing technology for UHS that will keep scaling in the coming years [6].

2.3. Salt Caverns

Salt caverns are currently considered to offer the most promising underground storage option owing to their low cushion gas requirement, the large sealing capacity of rock salt, and the inert nature of salt structures, preventing the contamination of the stored hydrogen. The geometry of these structures is usually cylindrical. Salt caverns are artificial pits in thick underground salt deposits made from the surface by introducing water into a well in the salt rock, a process termed solution mining. Considering the requirements (and technical scope), they can be made up to 2000 m deep and have a volume of 1 Mm^3, a height between 300 and 500 m, and around a 50–100 m diameter, enabling them to store gas in massive quantities. Figure 3 illustrates these structures based on sonar measurements, as well as a general layout of the depths at which they can be built, showing it is possible to have a shallower storage reservoir when compared to oil and gas fields.

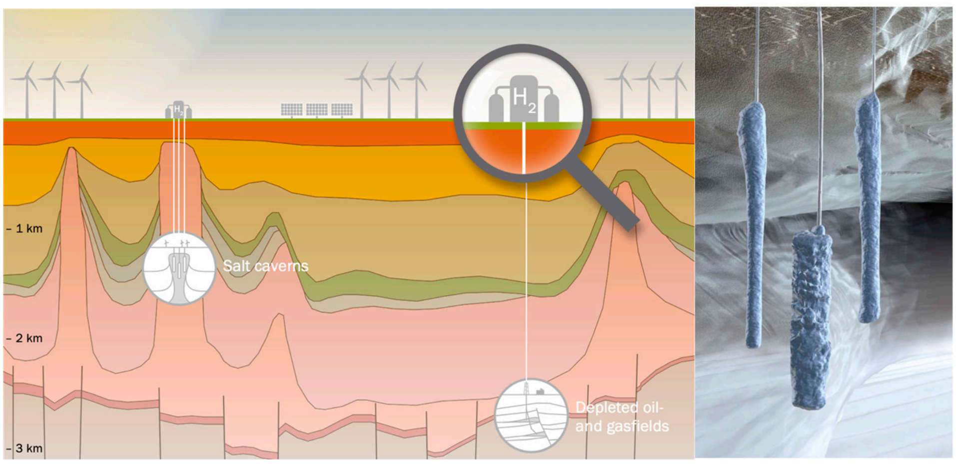

Figure 3. Schematic illustration of the depths of salt caverns and depleted oil and gas fields (**left**). Representation of three salt caverns surrounded by salt, based on sonar measurements (**right**) [8].

The main parameter determining their capacity is the depth. A higher cavern depth leads to more pressure and, in turn, more compressed gas, while lower amounts of cushion gas are needed at a lower depth, which helps reduce the operation's cost. Usually, for UHS in salt caverns, the pressure during the process ranges from 30 to 80% of the lithostatic pressure (i.e., the pressure imposed on a stratigraphic layer by the weight of overlying layers of material) [1,2]. The specific geological settings, including tightness, the praiseworthy mechanical properties of salt, and its low reactance make salt caverns practical for UHS. Additionally, the high saline environment restricts the hydrogen consumption by microbes.

Other advantages of salt cavern storage options include flexible operations, high injection rates, and faster withdrawal cycles. The viscoplastic characteristics of evaporitic rocks contribute to their better sealing function and, taking into account that salt caverns are mechanically stable, make the injection–withdrawal process more flexible and adequate for medium- or short-term storage.

From the economic point of view, the total cost to create salt chambers is lower than for other underground formations and less than for aquifers and depleted oil and gas reservoirs, as all these processes are built from the surface through a single well. This well use during the injection and withdrawal periods makes salt cavern storage facilities easy to manage, allowing for the gas to be injected and extracted several times per year. The actual implementation of the structures in gas storage (other than hydrogen) proves that these are ideal for keeping peak-time gas reserves.

The extensive experience gained by projects worldwide allows salt cavern developments to have as many as sixty-three underground formations. This was achieved in Jintan, Jiangsu province, in China, where this facility has served as an underground gas storage (UGS) site since 2007 [9].

These characteristics endow salt caverns with long-term stability. Experts have concluded that these deep geological formations are the safest and most economically viable for implementing UHS, storing large volumes of electrical energy after conversion into hydrogen or methane. Their recommendation is mostly due to the many decades of positive operating experience as underground storage reservoirs for natural gas [10].

2.4. Parameters

It is crucial to characterize the sites for UHS and to have a solid reference for better results when developing them. The parameters presented while explaining each geological structure's advantages and disadvantages should be organized and fulfill a standard. To date, there is not an organization that regulates UHS, nor a particular reference to look at. Thus, this subsection discusses the most influential parameters falling into three categories: the solid properties, fluid properties, and solid–fluid (and fluid–fluid) interactions.

The solid properties of the storage medium are crucial factors that influence the UHS storage capacity, storage effectiveness, and containment security. Among them, absolute permeability (k_a) is the ability of a porous medium to transmit fluid (when the porous medium is 100% saturated by this fluid). The effective porosity ($\phi_{\text{effective}}$) is defined as the ratio of the connected pore volume to the bulk volume, which determines the maximum storage capacity. The effective stress ($\sigma_{\text{effective}}$) is defined as the difference between the overburden (or overcharge) pressure and pore pressure [11].

The fluid properties are also critical parameters that strongly influence the UHS effectiveness and safety. Because these were previously discussed, they are omitted in this subsection. Nevertheless, these parameters should always be considered and reviewed in detail for each case. Some chemical reactions may or may not occur depending on the particular site and location.

The last category proposed is the solid–fluid and fluid–fluid interactions. Although these are related to the solid and fluid properties, the interactions fall into a separate category because they characterize different aspects of UHS: fluid distribution, fluid migration, gas adsorption, chemical reactions, and reactive transport. The interactions require work on their own, as they follow complex mathematical models, and computational calculations are the only way to analyze the data. Although some preliminary work has been completed, and some data are available, it is clear that this category needs to improve its specifications to succeed with the plan for standardizing UHS. The following parameters in this category are mentioned as areas to cover and develop in future investigations and projects: the wettability, interfacial tension, capillary pressure and capillary forces, relative permeability, mobility ratio, absorption–desorption, inorganic reactions, and biochemical reactions. Although similar to other gas storage (e.g., the natural gas case), UHS does not share the same reference values for this last category. Therefore, extrapolation from these different scenarios must be avoided [11].

Figure 4 shows the mentioned influential parameters for future UHS systematic site characterization and standardization. Figure 5 shows how each type of geological structure suitable for UHS performs for some relevant operational parameters.

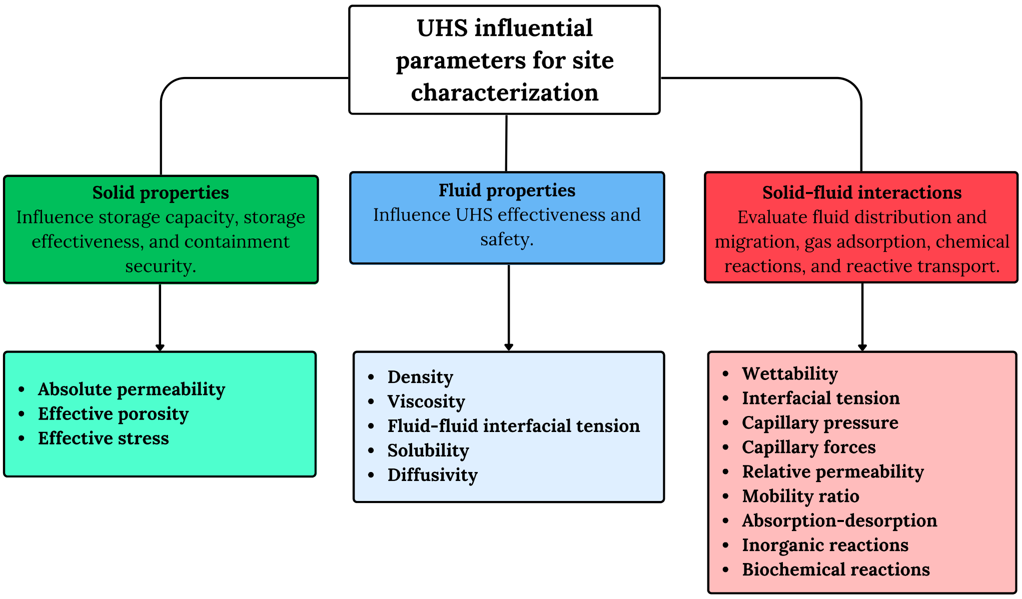

Figure 4. The most influential parameters for future UHS site characterization and standardization. Adapted from [11] with permission from Elsevier.

Figure 5. Comparison of selected operational parameters of geological structures suitable for UHS.

2.5. Seasonal Storage

Seasonal energy storage refers to capturing and storing energy during excess supply or low demand, typically during certain seasons. The stored energy is used when the demand is higher, or when the supply is limited. It involves storing energy for an extended period, usually spanning months, to address the seasonal variations in energy production and consumption. This energy consumption varies with the demand, depending on daily and seasonal changes or emergencies, while the energy production is usually constant. The excess electricity produced is converted to hydrogen to regulate these fluctuations and is temporarily stored and used later when the consumption exceeds the production, a process known as Power-to-Power [1]. Energy storage will play a key role in providing the required system security, flexibility, and adequacy in the future integration of hydrogen into the energy system. Stability refers to the response to short and fast fluctuations in the power system. Flexibility corresponds to the response to load and supply changes up to the seasonal timescale. As for the ability to adjust to long-term trends and emergencies, this is called adequacy. Supply and demand patterns influence the energy system on different timescales, demanding different solutions. Therefore, more significant energy storage deployment is predicted at these different scales. As seen in Figure 6, the need for a portfolio of energy storage solutions that exploit the advantages of each storage technology and altogether deliver the needed systems services is clear [8].

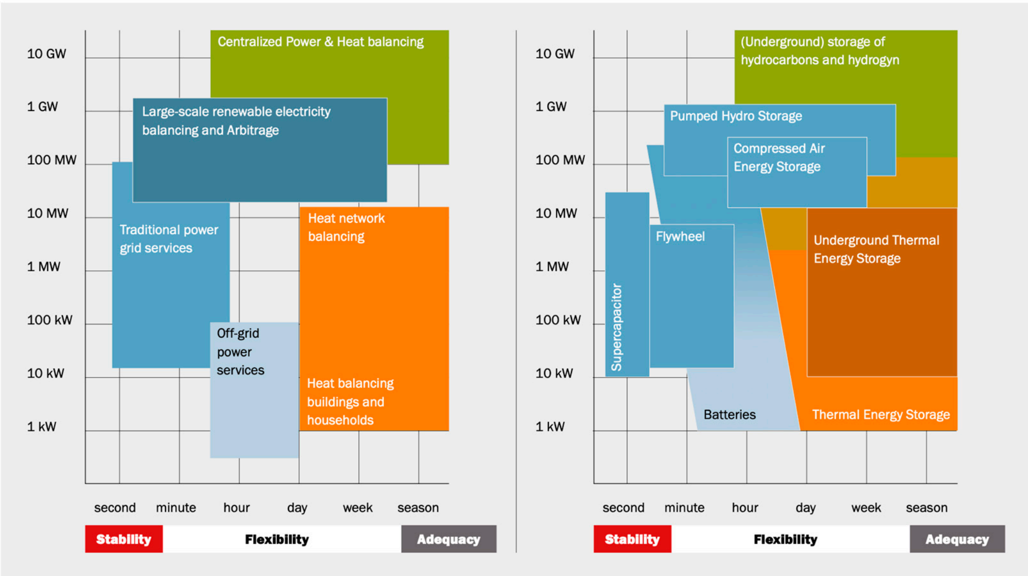

Figure 6. Energy system services and storage options mapped according to their power and relevant timescales (charging and discharging). The color indicates the infrastructure system in which it is implemented: (blue: electricity grids; green: gas infrastructure; orange: heat networks) [8].

Furthermore, hydrogen production via water electrolysis using surplus wind energy with its high-energy yield ratio can enable a wider utilization of wind energy, offset costs, and balance supply variability. As noted, this leads to heavy short-term fluctuations in electricity prices and subsequently to short-term fluctuations in mainly the hydrogen supply from electrolysis, and, therefore, to a need for absorbing this produced hydrogen in storage facilities. Significant experience has been gained through a number of small-scale renewable hydrogen systems [12]. UHS offers a feasible clean energy storage option, leaving free surface area to install more capacity (wind, solar, or other technologies) and creating massive energy reserves for future long-term trends and development.

Considering the use of surplus energy (mostly from wind and solar energy production) for green hydrogen production through electrolysis and then for its underground storage, the energy industry and others are awaiting information on the possibilities in this regard [13]. Figure 7 helps illustrate how UHS could help compensate for peak demands and make up for seasonal patterns. Looking at the red line on each graph, one can observe how the demand stays more or less constant with its respective peaks compared to the solar and wind resource variability. Thus, intermittent renewable electricity output is a problem that can be solved by dealing with another one: the excess power generated by wind and solar parks when the demand is low. This extra energy needs to be stored so that it can be made available during peak periods. This can be accomplished by using this surplus electricity to split water into oxygen and hydrogen through electrolysis. Electricity is then converted into hydrogen as molecules that can be stored. Thus, hydrogen works as an energy carrier. The gas can be transported in large quantities safely and invisibly to the underground infrastructure and stored in an environmentally friendly manner in the different geological reservoirs, without sacrificing surface area. This storage significantly contributes to secure supply and allows for economic growth. Section 3 discusses how proper sites for UHS can be found.

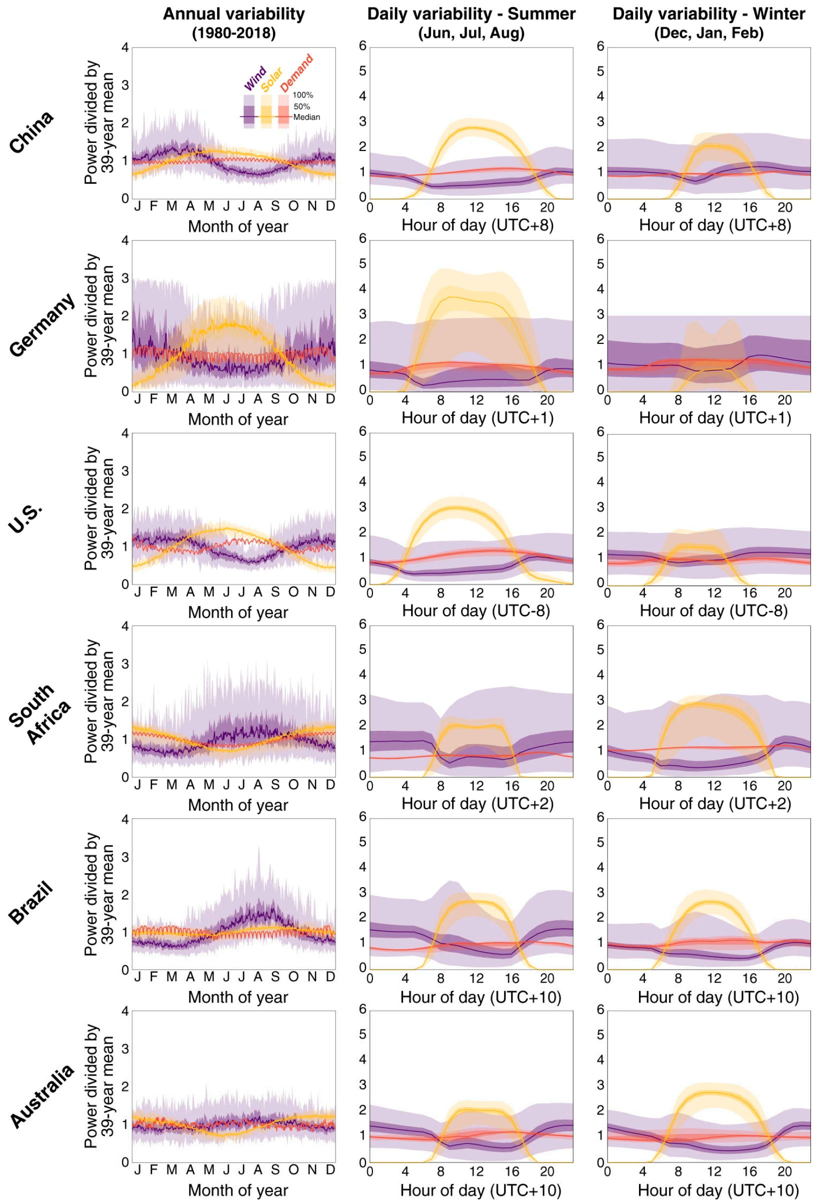

Figure 7. Temporal variability in solar and wind resources and electricity demand for different countries, showing the annual variability (left column) and the daily variability in summer (middle column) and winter (right column) [14].

3. Site Selection

In 2018, M. Deveci proposed, for the first time, the use of multi-criteria decision making (MCDM) for UHS site selection [15]. As UHS is a technology that requires the simultaneous evaluation of multiple parameters, the MCDM approach presents a perfect tool for evaluating UHS prospects and identifying the optimal locations for future developments. MCDM is a decision method that involves selecting the best option from a set of alternatives according to more than one factor, depending on the condition of the decisionmakers, according to the following steps:

1. Problem identification: define the decision problem and establish the objectives and criteria relevant to the decision;
2. Criteria selection: Select the criteria that will be used to evaluate the alternatives. These criteria should be measurable, relevant to the decision, and reflect the objectives;
3. Weighting of criteria: Assign relative weights to each criterion reflecting its significance. Weights indicate the relative importance of each criterion in the decision-making process;
4. Alternative generation: generate a set of alternatives that could potentially address the problem;
5. Evaluation of alternatives: Assess each alternative. This may involve quantitative analysis, qualitative assessments, expert opinions, or a combination of approaches;
6. Scoring and ranking: assign scores or ratings to each alternative based on their performance or suitability with respect to the criteria;
7. Decision analysis and decision making: analyze the scores or rankings of the alternatives to identify the best or preferred option.

The main and sub-criteria for selecting UHS sites (specifically for salt caverns) are proposed in Table 2 [15].

Table 2. Main and sub-criteria for selecting UHS sites. Adapted from [15] with permission from Elsevier.

Main Criteria	Sub-Criteria
Technique characteristics	Type of storage Reservoir depth Storage capacity Gas pressure Reservoir porosity and permeability Geology Reservoir thickness
Costs	Storage cost Investment cost
Socio-economic characteristics	Environmental and public Proximity to suppliers and resources
Risks	Ground features Life expectancy Regional location and risks

To form matrices for the MCDM would require analyzing specific options and sites. Although this is out of this review's scope, future works may use this methodology to assess the possibilities. Potential UHS sites should follow this approach for the technology to succeed. Achieving good results in the coming UHS facilities will play a vital role in the evolution of these storage options, providing confidence to future investors. The poor selection of an underground storage site for hydrogen could have irreversible consequences and adversely impact the economic viability of these storage processes [15].

Other methodologies for site selection have been applied. Caglayan et al. [2] proposed the approach shown in Figure 8 to develop a salt cavern "field" (i.e., simultaneous caverns on the same site). Even though it considers most of the aspects mentioned for MCDM, no weight is given to any of them, leading to a more technical decision, leaving aside the socio-economic and risk characteristics. This highlights the benefits of using MCMD in UHS site selection.

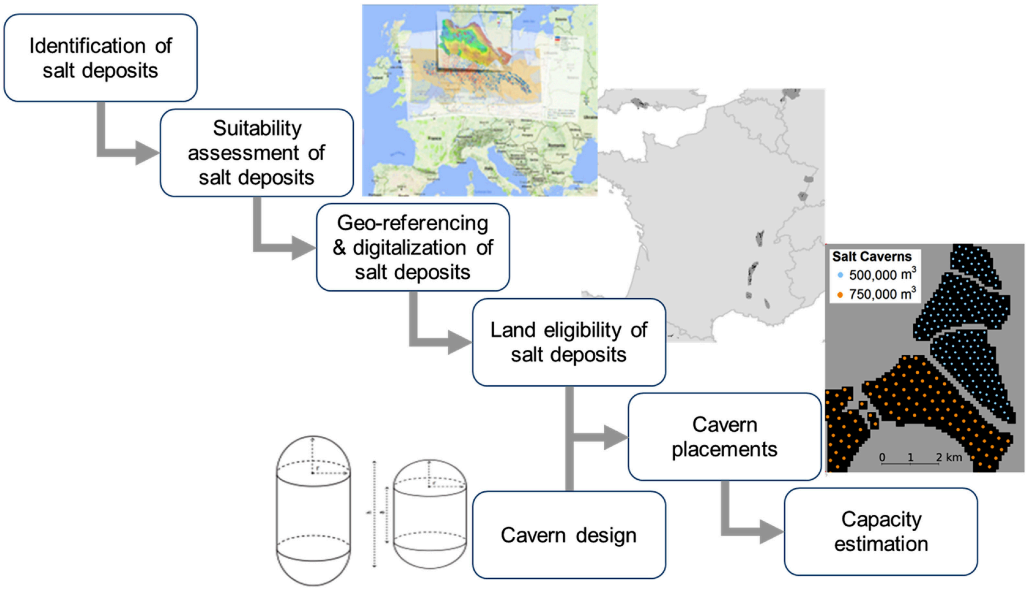

Figure 8. Alternative site selection methodology for salt caverns. Reprinted from [2] with permission from Elsevier.

Many criteria, such as geological, engineering, economic, legal, and social issues, are critical in the gas storage operation. These parameters are used to study the feasibility of UGS operation. Amongst them, geological criteria are the primary concerns and are not adjustable. They could affect the operational cost, operation efficiency, and involved risks. Thus, geological criteria are the primary concern and must be prioritized during site selection.

4. Technical Challenges Ahead

Every aspect of UHS still needs to be improved in the coming years. Various issues related to the technical challenges of UHS have to be dealt with by following the current recommendations from the experts in the field [1]. The main issues to be considered relate to site characterization, injection strategies, biological, geochemical, and bacterial effects, mechanisms and monitoring, and withdrawal strategies.

4.1. Site Characterization

Setting the requirements and conditions for choosing the optimal geological structure for UHS is a multifaceted process and should be based on detailed geological analysis and reservoir engineering. The site must feature the right reservoir properties, primarily porosity and caprock integrity. Optimal reservoirs consist of porous rock, usually sandstone, offering high porosity, translating to maximum hydrogen storage capacities [16]. However, it is equally essential that these formations exhibit adequate permeability to enable the efficient injection and withdrawal of hydrogen. Moreover, the caprock, which sits atop the porous reservoir, must be reasonably thick and impermeable. This impermeability is crucial to prevent any risk of hydrogen leakage into adjacent geological layers or to the surface [17].

The site's location also plays a critical role in determining the economics and feasibility of the storage operation. Factors such as the site availability, proximity to existing pipelines for hydrogen transport, and access to hydrogen sources significantly impact the overall viability of the project. Sites situated close to hydrogen sources and existing pipelines often yield more favorable outcomes in terms of operational efficiency and cost effectiveness.

Ensuring the integrity and tightness of the caprock is paramount; it acts as a seal, effectively preventing gas migration into adjacent geological layers and formations above. Common caprock materials, such as salts and clay layers, have been recognized for their efficacy and hydraulic integrity when subjected to the presence of hydrogen [18].

Recent research on hydrogen storage as a solid hydrate has gathered considerable interest. Hydrate-based storage technology is expected to be superior to other alternatives given the higher density, complete reversibility potential, safety storage within the water lattice, and cost reduction. Therefore, locations that meet the conditions for stabilizing hydrogen hydrate or that could be adapted in a more feasible way should be explored. Zhang et al. [19] state that such conditions include low temperatures and relatively high pressures (hydrogen hydrate is formed above 2.3 GPa and is stable at 300 MPa and 280 K), but the available data are old and limited to atmospheric pressure. Overcoming this lack of information could expand the list of suitable geological structures in which the temperature gradient allows for the required stability [20]. These may include pressurized shallow caverns, ice caves, sea ice caves, ice cracks, glaciers, or permafrost.

4.2. Injection Strategies

Efficient hydrogen injection into the underground relies on optimizing well patterns and injection rates [21]. The placement of multiple injection wells beneath the caprock is a key strategy for conserving a significant amount of hydrogen and reducing the risks of lateral spreading, dissolution, and viscous-fingering effects. These issues can lead to losses and a decreased overall storage efficiency.

Controlling the injection rates is equally crucial. High injection rates can result in fingering and lateral spreading, leading to the loss of hydrogen. Maintaining a low and consistent injection rate promotes a stable front, reducing the chances of hydrogen losses. Moreover, low injection rates allow enough time for the fluid to dissipate along the fault plane, reducing the probability of seismic events [17]. Ensuring that the injection rates and pressures remain within specified limits is imperative. This prevents exceeding critical thresholds like the fracturing and capillary entry pressures while maintaining an adequate safety margin.

Another important technical challenge is related to cushion gases. Selecting an appropriate one is a decisive aspect of successful UHS, and proper consideration optimizes the storage process (i.e., it has been proven that increasing the molecular weight of the cushion gas decreases the UHS performance) [4]. While nitrogen is often considered due to the lower initial investment costs, its higher viscosity and density (compared to hydrogen or methane) must be accounted for (e.g., aids in displacing water efficiently). During cyclic operations, the intense mixing of hydrogen and nitrogen can occur, affecting the storage performance. An alternative cushion gas option is carbon dioxide, primarily chosen because of its greater density than hydrogen under typical reservoir conditions. However, even in low concentrations, it may promote the dissolution of the cement seal and reduce the overall well integrity [22].

Additionally, there is a general concern regarding the hydrodynamic effects. Understanding and managing them is essential for stable UHS, as these can lead to unstable displacement and uncontrolled gas leakage. Gravity forces can stabilize the displacement and decrease spreading and fingering, leading to an overall improvement in the storage efficiency. Reservoir features like steeply dipping structures and thick sands can help prevent unwanted gas movement [23].

4.3. Biological, Geochemical, and Bacterial Effects

The presence of CO_2, ${SO_4}^{2-}$, Fe^{3+}, and clay minerals like Kaolinite, Illite, and Feldspar greatly impact UHS. CO_2 can lead to methanogenic and acetogenic reactions, converting hydrogen into methane, and causing energy loss [24]. Effective control methods, like the introduction of small amounts of gaseous oxygen, can prevent the growth of methanogenic archaea [25]. For sulfate reduction, caused by ${SO_4}^{2-}$, maintaining preferable temperatures of up to 92 °C is crucial. Iron (III) reduction to iron (II) due to Fe^{3+} can also impact hydrogen storage and should be managed in reservoirs [26]. Furthermore, clay minerals present in caprock and reservoir rock can induce precipitation and dissolution reactions, affecting the porosity and permeability. Monitoring these reactions helps maintain the reservoir integrity.

4.4. Mechanism and Monitoring

Being able to control and monitor implies understanding the mechanisms behind gas mixing, losses, and leakage. Gas mixing can lower the recovered gas quality through the co-production of cushion gases or pre-existing gases. Effective control involves selecting cushion gases with significantly different densities from hydrogen and maintaining low injection and withdrawal rates. Losses may occur due to viscous fingering, hydrogen trapping, conversion into other gases, or interactions with minerals [27]. The appropriate injection rate, consideration of pre-existing fluids, and understanding of rock mineralogy can minimize these losses, with less than 5% typically deemed acceptable [1]. Leakage in water-saturated caprock, though limited, can be prevented by using water-wet caprock with high capillary pressure thresholds.

4.5. Withdrawal Strategies

The efficient withdrawal of stored hydrogen relies on optimizing well patterns and rates. The strategic placement of shallow extraction wells beneath the caprock enables the recovery of significant quantities of hydrogen while enhancing both the injectivity and withdrawal. Highly permeable zones can further boost the performance. However, maintaining a high withdrawal rate can lead to fluid coning, pressure drops, and a reduced overall efficiency. In aquifers, excessive water production may occur alongside hydrogen extraction. Therefore, controlling the withdrawal by maintaining constant pressure in the well is advised. The cycle duration, rate, and number of withdrawal cycles significantly affect the storage performance. Increasing the number of cycles enhances the storage performance, while longer durations between cycles allow for the gravitational separation of fluids, improving the overall efficiency. A necessary process to ensure feasibility and economic viability is to remove impurities from the withdrawn gas during the withdrawal stages [21].

5. Past Experience and Ongoing Projects

After overviewing how UHS is technically possible and the aspects to be improved in the upcoming years, the final sections focus on the feasibility of UHS studies that have been carried out in Canada, Russia, Romania, Germany, the Netherlands, the United States, Spain, Poland, China, Turkey, and France. Most of these investigations have focused on the use of salt caverns. Their many favorable properties for UHS make them the only storage option currently in use for geological hydrogen gas storage, serving industries in the United States and the United Kingdom.

The Hydrogen Technology Collaboration Programme, or Hydrogen TCP, was established in 1977 under the International Energy Agency's auspices to promote collaborative hydrogen R&D and information exchange among member countries. To date (June 2023), it comprises 26 Contracting Parties (24 countries, the European Commission, and UNIDO) and 7 Sponsor Members. Seven parties reported kickoffs on the UHS implementation in the Hydrogen TCP 2021 Annual Report [28] (Table 3). The growing interest in the technology has been brought to the committee's attention, achieving in the Hydrogen TCP 2022 Annual Report [29] a new task dedicated to UHS named "task 42".

Task 42 focuses on research and innovation challenges. It embodies a global community of 54 organizations and over 190 specialists spanning industry, scientific and academic institutions, and government spheres dedicated to realizing and implementing UHS as a technically, economically, environmentally, and societally viable technology in the future sustainable energy system. Task 42 is subdivided into six subtasks that cover the full spectrum of challenges, from geological research and engineering to economic evaluation and social aspects. Among the resources consulted in this work, Task 42 contains the most complete and updated information, showing that this effort lays a strong foundation for the future of UHS. Upcoming works must find a firm reference on the current state of UHS reported by this community.

Table 3. Reports on UHS for members of Hydrogen TCP in 2021 based on data from [28].

Member	Report on UHS
Austria	Work for the underground storage of pure hydrogen has started.
Canada	Proposals were submitted in 2022 to allocate another USD 2.6 million per year until 2026 on the hydrogen embrittlement of pipelines and well integrity concerns for in situ hydrogen production and UHS in geological formations.
France	Objectives include ensuring access to natural gas transmission and distribution infrastructure, establishing prerequisites for UHS, and creating a system for assuring and monitoring the hydrogen source traceability.
Germany	Three living laboratory initiatives have started, focusing on producing green hydrogen, subsurface storage, and industrial use (H2-Wyhlen, Energiepark BL, H2-Stahl).
HyChico (Argentina)	Hychico has undertaken multiple high-performance projects, including over 85,000 operational hours of a Genset powered by natural gas–hydrogen blends, UHS in depleted gas reservoirs, and bio-methanation processes. Given the proximity of the hydrogen plant to depleted oil and gas reservoirs, a UHS pilot project in one of them is under consideration.
The Netherlands	The Hyway27 study reported that repurposing existing gas pipelines is safe and cost effective (4 times less expensive than building a new infrastructure), enabling the creation of a hydrogen infrastructure backbone. A total of 1200 km of hydrogen pipelines for UHS are projected by 2027.

Thirty-three planned or operating hydrogen gas production projects worldwide have quoted capacities over 1 MW. The data presented in Appendix A are based on the report by van Gessel and Hajibeyg [30], complemented with information from Miocic et al. [3], and this appendix gathers documented projects or proposals that target the establishment of sites where UHS will be assessed, verified, or implemented. Notably, the majority can be found in Europe. Table 4 displays the four known sites where pure hydrogen (at least 95%) is currently stored in salt formations for industrial commercial purposes. Figure 9 shows these sites' locations in the United States and the United Kingdom. These initiatives play a huge role in broadening UHS on a larger scale, as they are pioneers in overcoming technical, economic, and social barriers, contributing to implementing net-zero energy systems.

Table 4. Main features of the first four pure hydrogen storage facilities. Adapted from [30].

	Clemens Dome (U.S.)	Moss Bluff (U.S.)	Spindletop (U.S.)	Teesside (U.K.)
Operator	Conoco Phillips	Linde	Air Liquide	Sabic
Start of operations	1986	2007	2014	1972
Geometrical volume (m^3)	580,000	566,000	>580,000	3 caverns, 70,000 each
Pressure range (bar)	70–135	55–152	68–202	45
Mean cavern depth (m)	1000	1200	1340	365
Net energy stored (GWh)	92	120	270	25
Working gas (ton H_2)	2400	3700	8200	800
Net volume (std m^3)	27.3	41.5	92.6	9.12
Working gas (MM scf)	960	1450	3250	320

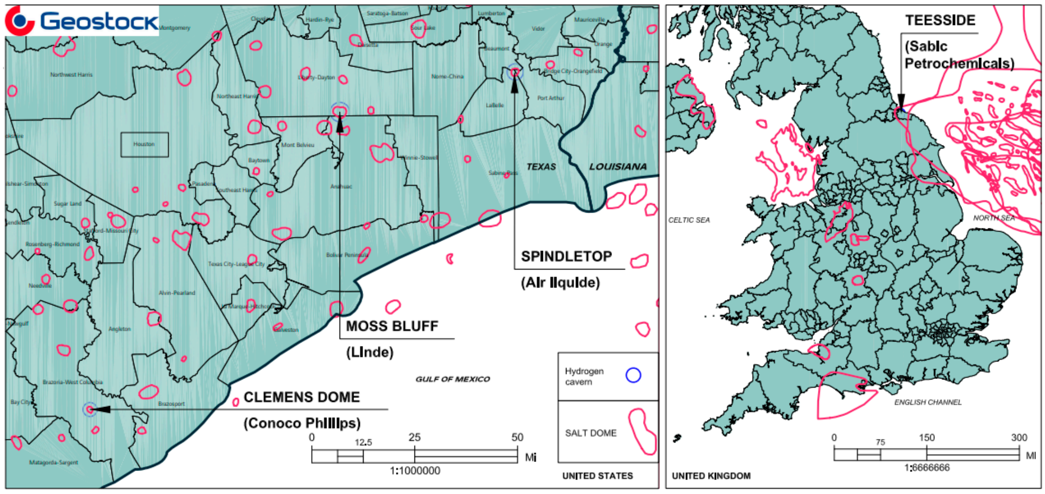

Figure 9. Locations of the first four (three in the U.S. and one in the U.K.) pure hydrogen storage facilities [30].

Other remarkable initiatives include two operational pilot facilities (Austria and Argentina) where injection and withdrawal tests have been conducted with 20% hydrogen and 80% natural gas mixtures in depleted gas fields. Another case is a pilot facility for pure hydrogen storage in a small, depleted gas reservoir deployed in 2023 in Austria, which is different from the one reported in the Hydrogen TCP 2021 annual report.

6. Market Size

Beyond individual efforts, international cooperation is crucial to align objectives, increase the market size, promote knowledge sharing, and develop best practices. International cooperation related to hydrogen has remained strong over the last years. It is expected to accelerate as a consequence of the Russian invasion of Ukraine and growing concerns about energy security. This event has conditioned the supply and price of natural gas. The hydrogen price for the industry is strongly correlated with the market price of natural gas [31]. Since September 2021, fifteen new bilateral international agreements between governments have been signed, focusing on the development of the international hydrogen trade [32]. Governments, particularly in Europe, are looking at opportunities to accelerate the commercial availability of hydrogen technologies and the growth of international trade to reduce the dependency on fossil fuels as fast as possible. Moreover, European institutions are actively signing international agreements with non-European governments seeking to facilitate investment and accelerate the development of international supply chains. The entry of U.S., Chinese, and Japanese companies to the hydrogen sector in Europe will accelerate the UHS project development, especially because of the pilot projects they have already developed in their countries and the already operating sites they count (sites in the U.S.), inheriting all the experience gained with this.

Figure 10 shows potential sites in Europe where the mentioned companies could develop their UHS projects, along with the energy densities of the sites. Offshore locations are considered because of the growing offshore energy industry (tidal, marine currents, and especially wind). This will undoubtedly generate a surplus at some point, mainly in countries adopting and leading the technology (offshore) and with geographical advantages, like Norway, the Netherlands, and Portugal.

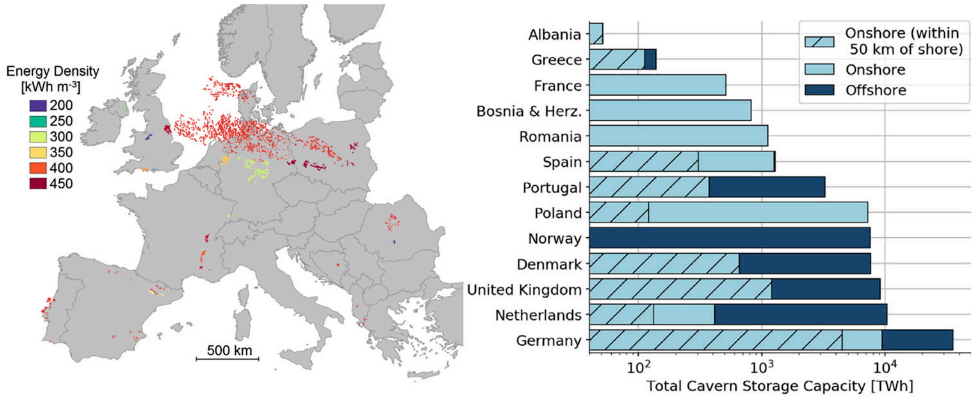

Figure 10. Distribution of potential salt cavern sites across Europe with their corresponding energy densities (**left**) and total cavern storage potentials in European countries (**right**). Reprinted from [2] with permission from Elsevier.

Developing efficient and cost-effective methods of deploying UHS is a priority for industry and scientists focusing on large-scale hydrogen production. Such demand comes from the need to meet the goals of faster technology deployment, as projections for hydrogen production and end uses anticipate a six–seven-times increase from 2020 to 2050 [30]. However, the expected demand for storage remains uncertain towards 2050; the required volumes will likely be comparable to or surpass the operational capacities for underground natural gas storage. The following points list significant constraints and barriers to generating feasible business scenarios linked to UHS technology.

1. Purity requirement for hydrogen grids: The viability of business cases related to hydrogen injection into transport pipelines will be impacted by quality specifications, primarily driven by purification costs. It is noteworthy that purification expenses tend to be higher for depleted fields than salt caverns;
2. Immature market for hydrogen storage: The demand for large-scale pure hydrogen storage has not yet been established. While this demand will arise in the coming 10–20 years, the forecasts and expected application areas remain unclear. Consequently, there is no clear insight into the future UHS business case and how the returns on investments will evolve. This hinders investors from committing to long-term investment decisions, resulting in delays in the progress of viable cases. The type of market regulation (regulated vs. third-party) on UHS development should be examined;
3. Lack of experience in UHS operations: the practical experience with high-purity hydrogen storage has been confined to just a handful of salt cavern storage sites;
4. Availability and knowledge of suitable geological structures: The assessment and ranking of viable geological reservoirs is still in the early phases. Selecting and improving potential site identification might need significant financial support for exploration, appraisal, sampling, and testing. Moreover, an uneven distribution of salt deposits, hydrocarbon reservoirs, and aquifers could restrict the prospect of developing economically achievable scenarios.

Some positive points to UHS are the growing investment trends in hydrogen technologies; more equipment that needs hydrogen means more hydrogen demand. The global hydrogen review of 2022 by the International Energy Agency [32] highlights the enhanced flow of capital to certain key hydrogen technologies via project investment and equity in companies for scale-up. The accelerated pace is fueled by numerous converging factors, including the acknowledgment that the energy transition to net-zero emissions is quickening and that hydrogen's role in meeting this target is expanding, partly due to technological advances. In 2021, hydrogen-focused companies raised record amounts of capital regardless of a sharp drop in estimation related to wider economic concerns. It is becoming more encouraging for large projects to break ground soon, spurred by recent initiatives and ambitious goals in the European Union to replace natural gas consumption. One example of this trend is seen in Figure 11, which shows how much more was invested in 2021 in electrolyzer installations than in any previous year, corresponding to almost 210 MW and an estimate of more than USD 1.5 billion.

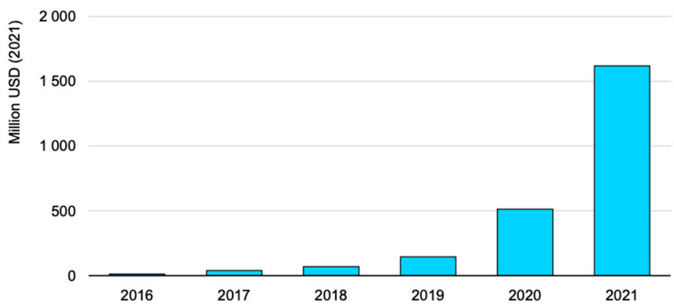

Figure 11. Annual investment in electrolyzer installations since 2016 [32].

Other companies with hydrogen-related technologies follow the same trend for different aspects of the hydrogen economy. Figure 12 shows that innovative companies with hydrogen-related technologies secured record financial support between 2015 and 2022. The applications include fuel cells, hydrogen storage, hydrogen-based fuels, and vehicles, showing that the hydrogen economy is becoming stronger.

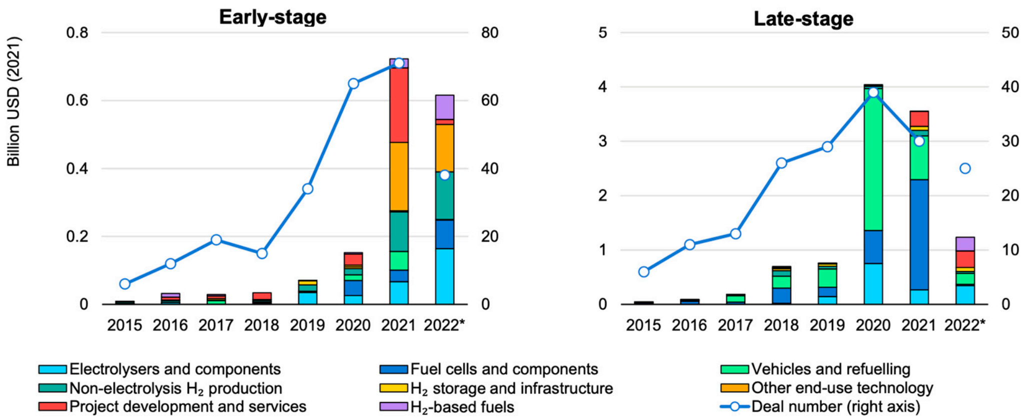

Figure 12. Venture capital investment (in USD billion) in clean energy startups related to hydrogen in 2015–2022. * Values for 2022 only include preliminary data for deals up to June 2022 [32].

7. Infrastructure

To develop a hydrogen economy, there must be a significant upscaling in subsurface storage. As seen, there are various approaches, with different ways that this upscaling can happen; each has cons and pros, and each is in different stages of development: some are proven, some are not, and some can store higher volumes of hydrogen, and some cannot. To achieve the goals of humankind, UHS is the first step to accelerate the transition to a net-zero future. UHS sites could repurpose current infrastructure components (e.g., platforms, pipelines, wells) depending on the adaptability of these elements. One of the great advantages that hydrogen has is its compatibility with existing infrastructure. To what extent can existing infrastructure be repurposed? As shown in Appendix A, some sites have already started working on this, and the results on cycle loading, the performance of the wells, or the potential damage to the equipment will arrive sooner than later.

For the less explored options like aquifers, larger infrastructure will be required for its implementation in the hydrogen net. If such infrastructure must be built from zero, it may significantly impact the CAPEX (i.e., the capital expenditure). Furthermore, the technology readiness level of equipment and the specific facility elements for UHS (e.g., compressors, purification) are still in an early stage. But again, their implementation will become (and is becoming) faster.

Some legal aspects of the technologies still need to be dealt with, especially those regarding social perception and acceptance. For example, it might be more difficult for a lawyer to read a technical report than someone with a background in engineering. With growing international interest, hydrogen has been involved in several EU policies and legislation, and it will most likely be included in many initiatives to come. Legal and regulatory frameworks for UHS (permitting, planning, visions on upscaling, market development, norms, and definitions) are yet to be officially defined within the existing juridical and economic framework, demanding establishment at such a level that current technical advances in the social context can be embedded. Therefore, UHS investors face uncertainties concerning the extent of their operations and, at last, their capacity to achieve the anticipated return on investment in the long term. Additional doubts may arise due to the limited engagement of stakeholders and lack of public and/or political acceptance and support.

The work left to accomplish is to spread the word on the benefits of moving to the hydrogen economy, continue researching and promoting hydrogen use, read the latest reports, and work hard on this promising technology.

8. Conclusions

The quick expansion of renewables and decarbonization strategies has led to a worldwide demand for specific development plans for large-scale energy storage solutions, including deep underground geological formations, like rock and salt caverns, or porous rock reservoirs encompassing saline aquifers and depleted gas fields. The anticipated surge in hydrogen needs, to be satisfied through renewable energy sources and with little environmental impact, underscores the necessity for large-scale hydrogen storage solutions. These will be essential to address the variations in the energy production and consumption patterns across daily–seasonal timeframes and to strategically ensure energy availability. Global forecasts estimate that the required storage volumes will surpass the existent operational capacities for subsurface natural gas storage and can only be practically achieved in the mentioned geological formations.

Thus, after reviewing the current status of underground/subsurface hydrogen technology, it has been found that, despite recent commercial developments, UHS is not yet ready for complete industrial and nationwide integration within the fast-evolving and decarbonizing energy system. The integration of UHS into the energy system framework is pending significant pilot programs and demonstration projects, which are crucial for addressing critical gaps in knowledge and verifying insights gained through laboratory research and numerical modeling in an actual underground setting. These efforts are equally necessary for increasing industrial expertise, assessing feasible business cases, and acquainting stakeholders and the general public with the benefits and repercussions of UHS.

UHS shares many technical aspects with UGS, involving the same type of underground reservoirs and similar principles for exploration and storage operations. In contrast, significant distinctions exist in the behavior of hydrogen in subsurface environments and in how this behavior may have far-reaching implications in the safety, sustainability, efficiency, and economic aspects of UHS deployment and operations. Because hydrogen naturally presents a high reactivity, it is prone to induce geochemical and microbial reactions. Considerable expertise has been acquired in the secure and efficient injection and containment of natural gas in underground structures. Lessons from storage endeavors on an industrial scale have demonstrated the successful confinement of pure hydrogen in salt caverns under conditions of minimal cyclic loading. Nonetheless, it is imperative to clear the existing knowledge gaps related to the adaptations required for individual facility components and wells.

Empirical data regarding the impact of hydrogen on the mechanical characteristics of reservoirs are minimal, as is the comprehension of the outcomes associated with rapid cyclic loading and unloading featuring high-pressure fluctuations, which are commonly encountered in UHS. Existing projects with salt cavern development and storage operations provide a relatively accurate approximation of the CAPEX and operational expenditures. However, the uncertainty of the cost estimation is still substantial for UHS in porous reservoirs. The site's specific characteristics heavily influence the project development expenses, as recently discovered sites require significant exploration and ripening efforts.

9. Future Outlook

This work has proven the enormous amount of work involved in combining several fields of study into one common objective. Moreover, much labor must be undertaken for UHS to become a reality in the short term, as is required. Developing specific solutions and concepts for the reutilization of existing wells and components, and ensuring their safety and effective hydrogen operation, are essential to guarantee the functionality and resilience of the materials and facilities. This also involves modifying existing facilities and legacy wells when repurposed for UHS operations. Purification technologies are crucial to meet the quality criteria of the hydrogen transport net and end users.

Additional insights must be garnered from practical storage initiatives to establish secure operational thresholds for swift cyclic loading. Expanding the empirical understanding of the incidence and consequences of geochemical and microbial reactions requires in situ and field-scale observations from pilot initiatives in diverse geological settings and operational scenarios. Enhanced forecasting and measurement of the processes can be expected by integrating public databases, standardized best practices, and monitoring instruments for testing, sampling, and performing analyses.

Quantitative experimental work and modeling studies are needed to evaluate the leakage and possible effects of geochemical reactions on the caprock integrity and the effective diffusion and spread of hydrogen in underground formations. In conjunction with field-monitoring data, these should encompass various rock types and realistic reservoir conditions, aiming to enhance the comprehension of the fracture generation and reservoir stability. Further improvement in multi-scale models for hydrogen transport in porous reservoirs is necessary. Models need validation through real-field experimental testing at a representative scale.

Conducting sensitivity analyses to quantify the most influential factors on the reservoir performance at a real scale is crucial. To increase the reliability, these should include measurements across different scales, geological settings, and operational conditions. Identifying and reducing uncertainties and investment risks is vital. By building experiences from multiple projects, the precision of cost estimates and potential profits from UHS will increase. Market assessment is needed to support UHS commercialization and upscale projects for generating long-term revenues, determining reasonable state-regulated prices/revenues for UHS, and establishing market regulation frameworks and conditions for early developments, given the absence of a market that supports commercialization and upscaling.

Future projects on UHS should develop the mentioned models, including conditions that are as real as possible. Appendix A summarize the current information on UHS development and research projects. However, before starting a new project, the most updated data on the performance and evolution of these projects are needed to avoid the same mistakes these pilot projects might make.

As a follow-up and complement to the present review, it is recommended to conduct research on the already existing sites that generate surplus energy (in more or less steady conditions) and match them with the locations for possible UHS solutions, making that study a tool for future business cases that look for innovative answers to their energy storage problems. The study of the cycle loading of the geological structures (particularly depleted hydrocarbon reservoirs) is also proposed, as the computational tools for this are already available (different universities' open codes) thanks to the long experience in UGS, geothermal resources, and even pumped hydro models.

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

Appendix A

Table A1. Overview of development and research projects.

Country	Project Name	Type	Expected Capacity	Development Status	Expected Start	Description	Source
Argentina	Hychico	Depleted gas field	Unknown (testing only)	Testing	n/a	Investigating storage of blended hydrogen (10%) in depleted hydrocarbon reservoirs, including geomethanation. Until 2018, the project focused on producing "green methane", and it seems to be changing to developing this technology.	[33]
Austria	Sun Storage 2030	Depleted gas field	Unknown	Construction	n/a	Aims to develop safe, seasonal hydrogen storage in depleted natural gas reservoirs.	[34]
	Sun Storage	Depleted gas field	Unknown (testing only)	Testing completed	2016	Experimental trials of injection of 10% hydrogen mixture in a gas field.	[35,36]
	Sun Conversion, FlexStore	Depleted gas field	Unknown (testing only)	Testing completed	n/a	Conducting experiments on underground methanation through the injection of hydrogen and carbon dioxide.	[37,38]
	HyStorage Bierwang	Depleted gas field		Testing	2025	Three operation phases using different natural gas/hydrogen gas blends (5, 10, 25 vol.% H_2 in natural gas) to be injected into the natural gas reservoir and withdrawn after a three-month holding period. First hydrogen injection in September 2023.	[39,40]
Belgium	Loenhout Hydrogen	Aquifer	2–3 TWh	Pre-feasibility	n/a	Tests with hydrogen–natural gas mixtures.	[41–44]
Denmark	Green Hydrogen Hub	Salt cavern	200 GWh	Pre-feasibility	2025	Aims to be the first viable commercial UHS with large-scale green hydrogen production and compressed-air energy storage.	[45,46]
France	Hypster	Salt cavern	3 tons	Construction	2023	E.U.-supported large-scale green UHS.	[47–49]
	Emil'Hy	Salt cavern	Unknown	Proposal	2023	Salt cavern in Cerville, Meurthe-et-Moselle department. Starting in 2023 with a production capacity of 5 MW, this project will build a new salt cavern in 2025 to support the increase in the production capacity, which should be in the 50–100 MW range by then.	[49,50]
	HyGreen Provence	Salt cavern	Unknown	Proposal	2028	H_2 will be stored within salt caverns at the Manosque storage site and distributed for different applications.	[49,51]
	HyGéo	Salt cavern	1.5 GWh	Pre-feasibility	2024	Constructed on a previous salt cavern site in a municipality within the Nouvelle Aquitaine region, the facility is designed to store 1.5 GWh of energy.	[49,52]

Table A1. *Cont.*

Country	Project Name	Type	Expected Capacity	Development Status	Expected Start	Description	Source
Germany	H2Cast	Salt cavern	Unknown (scalable)	Testing	2024	To showcase the viability of extensive UHS and demonstrate the suitability of salt caverns in Etzel.	[53,54]
	Jemgum Storage	Salt cavern	48 Mm^3	Pre-feasibility, FEED	2030	Evaluating the adequacy for UHS of a salt cavern used to store natural gas in Jemgum.	[55]
	HPC Krummhörn	Salt cavern	0.2 Mm^3	Pre-feasibility	2024	Project aiming for 100% hydrogen storage in the former Krummhörn natural gas storage site. The pilot facility is commissioned to store up to 0.25 M m^3 of H_2.	[56]
	Westküste 100	Salt cavern	Unknown	Pre-feasibility	n/a	A cavern storage system designed for UHS will use surplus wind energy to produce a continuous hydrogen stream for industry.	[57,58]
	Bad Lauchstädt	Salt cavern	150 GWh	Pre-feasibility	n/a	Green hydrogen is produced using an adjacent wind farm and temporarily housed in a salt cavern. Supplied to the hydrogen infrastructure of the chemical sector in central Germany, it is also envisioned for future urban transportation systems.	[59,60]
	GET H2 Nukleus Gronau-Epe	Salt cavern	67 GWh	Planning, permitting	2027	Plans include expanding the existing surface infrastructure to incorporate hydrogen injection, storage, and withdrawal systems in caverns. The facility will have 6 M m^3 of hydrogen in stock. An additional 28 M m^3 will be available for customers to store hydrogen.	[61–63]
	HyCAVMobil Rüdersdorf	Salt cavern	500 m^3	Construction	2023	Construction of the test cavern began in 2021 and finished in March 2023. It will be filled with hydrogen in 2023, and a "wet" hydrogen-drying system will be tested. Findings should be transferred to caverns with 1000× larger volumes. The main goal is to use caverns with 0.5 M m^3 for large-scale UHS.	[64]
Hungary	Aquamarine	Depleted gas field	Unknown	Construction	n/a	The Aquamarine project aims to deploy an electrolysis system with an estimated total capacity of 2.5 MW, as well as the associated hydrogen infrastructure, at the Kardoskut Underground Gas Storage site. The hydrogen produced will be blended with natural gas and employed in the Gas Storage Ltd.'s gas-operated equipment.	[65,66]
Ireland	Green hydrogen @Kinsale	Depleted gas field	3 TWh	Pre-feasibility	n/a	This project (pending license and planning approvals) will have a capacity of up to 3 TWh of green hydrogen and hydrogen carriers. An ample work program is underway, encompassing subsurface research, mineralogical studies, capacity modeling, injection and withdrawal rates, compression mechanisms, drilling assessment, well design, retention assurance, monitoring, electrolysis, and infrastructure integration.	[67]
Italy	North Adriatic Hydrogen Valley	Depleted gas field	Unknown	n/a	n/a	Evaluation of potential gas fields and aquifers.	[68]
Netherlands	HyStock	Salt cavern	6000 tons	FEED and permitting	2027	Initial borehole tests and demonstration in 2022. The first cavern will be operational in 2027, with a plan to upscale the capacity to four caverns by 2030.	[69,70]
Poland	Damasławek	Salt cavern	Unknown	n/a	2030	The first UHS facility to be operational in 2030. Placement and geological settings offer an opportunity to establish a storage site crucial to Poland's energy security and the base of a hydrogen economy. The facility is well suited to integrate hydrogen clusters created around industrial centers and offshore and renewable energy storage facilities.	[71]

Table A1. *Cont.*

Country	Project Name	Type	Expected Capacity	Development Status	Expected Start	Description	Source
Portugal	Sines H2 Hub, Carriço	Salt cavern	n/a	Pre-feasibility	2030	A significant industrial project is underway for the production of green hydrogen in Sines, which encompasses multiple aspects, including production, processing, storage (at Carriço), transportation (internal and export), and consumption.	[72–74]
Slovakia	H2I	Depleted gas field	n/a	Pre-feasibility	n/a	The initial stage of H2I S&D has experts searching for a suitable site for storing hydrogen blends (with natural gas). After the identification of the underground structure, lab studies will start.	[75]
Spain	Undergy	Depleted gas field	n/a	Pre-feasibility	n/a	Technologies for establishing long-term energy storage considering green hydrogen as a key part of the smart grid.	[76]
Sweden	HyBRIT	Lined rock cavern	n/a	Testing	2024	Pilot plant with a size of 100 m^3. Later, a full-scale hydrogen storage facility of 0.10–0.12 M m^3 will be necessary.	[77]
U.K.	Teesside	Salt cavern	25–27 GWh	Operational	1972	Pure hydrogen storage for industry feedstock supply.	[78,79]
	ANGUS+	Depleted gas field	n/a	Pre-feasibility	n/a	Studying the feasibility of connecting the Saltfleetby facility to the UK National Grid and exploring the potential for storage and methanation.	[80]
	HySecure	Salt cavern	Over 1000 tons	Pre-feasibility	n/a	Demonstration project for building a salt cavern for storing hydrogen at Stublach, the U.K.'s largest storage facility for natural gas.	[81,82]
U.S.	Clemens Dome	Salt cavern	81–92 GWh	Operational	1983	Storage of pure hydrogen for industrial purposes.	[78,79]
	Moss Bluff	Salt cavern	120–123 GWh	Operational	2007	Storage of pure hydrogen for industrial purposes.	[78,79]
	Spindle Top	Salt cavern	274 GWh	Operational	2016	Storage of pure hydrogen for industrial purposes.	[78,79]
	Advanced Clean Energy Storage	Salt cavern	300 GWh	FEED	2025	Two caverns, each with a capacity of 150 GWh, will store hydrogen produced by a close hydrogen-capable gas turbine combined-cycle power plant of 840 MW.	[83,84]

Table A2. Other relevant UHS research projects.

Country	Project Name	Description
Austria	BIOPore	Studying microbial growth and its implications from the pore to intermediate scales.
Europe	HyStories	Investigating UHS technologies for pure hydrogen storage in depleted fields and aquifers.
	HyUSPRe	Assessing the viability and possibilities of introducing the extensive storage of renewable hydrogen in European porous reservoirs.
	HyUnder	Assessing the potential actors and commercial frameworks for large-scale UHS in Europe (2012–2014).
France	Abiotic Reactivity of Minerals at Elevated H2 Concentrations	Examining fluid–rock alteration processes within deep aquifers pressurized with hydrogen.
Germany	HyInteger	Investigating the impact of microbial activity on the well structural integrity.
	H2 React and H2 React Phase 2	Research on fundamentals of UHS. The project aims to gather empirical data concerning the kinetics of chemical reactions, microbial activities, and hydrogen transport mechanisms within deep geological systems under in situ conditions.
	UMAS	The project examines the techno-economic and socio-economic viability and the ecological potential of underground methanation in aquifers.
	HyPos-H2UGS	Development of a standardized and transferrable procedure for constructing and converting salt caverns for UHS.
	TestUM-II Aquifer	Geophysical and hydrogeological field testing for investigating and monitoring reactive multi-phase transport processes in shallow aquifers induced by subsurface use. It is a continuation project of TestUM Aquifer.

Table A2. *Cont.*

Country	Project Name	Description
Germany	Bio-UGS	Investigating the reaction of green hydrogen with carbon dioxide to produce methane in subsurface storage systems using naturally present microorganisms.
	CliMb	Exploring the viability of conversion processes by combining experimental studies with numerical modeling and simulations in a multi-scale approach targeting from the micro- to macroscale.
Netherlands	ADMIRE	Multi-scale numerical–experimental studies of hydro-thermo-mechanics of UHS for the site choice and operation, based on high-PT hydrogen lab.
	Caves&Waves	Quantification of the probability of induced seismicity associated with large-scale hydrogen storage in Dutch salt formations.
	SafeInCave	Mechanics of salt cavern UHS and reservoir-scale simulator for evaluating the time-dependent salt cavern state of stress under cyclic loading.
	HyStoreReact	Aims to improve fundamental knowledge of UHS technical viability using salt caverns and porous reservoirs by examining the effects of geo- and biochemical reactions of hydrogen with rocks, fluids, and microorganisms on the subsurface.
New Zealand	PūHiko ukutū	Assessing the technical feasibility, cost effectiveness, and environmental and social impacts of large hydrogen storage (>50 M m^3) in sedimentary rock formations in New Zealand, specifically in the Taranaki Basin.
Norway	Hydrogeni	Center for supporting the development of a sustainable hydrogen economy in Norway and Europe.
	HyPE	Research on the physical and microbial processes that regulate the underground gas capacity, deliverability, and hydrogen injection rates in porous media. A numerical simulator will also be established based on lab data from hydrogen storage-related research.
	HyValue	Promoting knowledge, methodology, and innovative approaches for hydrogen energy carriers to shape and support a viable hydrogen energy sector.
	CSSR	Makes available required studies to address main adversities and create awareness of potential opportunities of reservoir operations in a net-zero future.
	Biorisks in Salt Caverns	Gaining critical information about halophilic microbes existing in salt caverns and their potential effects on UHS.
U.K.	GeoEnergy Observatory, Cheshire	An array of wells fit for the comprehension of the flow through porous rocks in an actual operational environment.
	HyStorPor	Investigating possible U.K. porous reservoir rock sites for hydrogen storage.
	IDRIC	Addresses crucial multi-disciplinary and cross-cutting challenges involved in decarbonizing industry, including UHS development.
U.S.	SHASTA	Evaluating the viability, safety, and consistency of the subsurface storage of 100% hydrogen or blends with natural gas.

References

1. Zivar, D.; Kumar, S.; Foroozesh, J. Underground hydrogen storage: A comprehensive review. *Int. J. Hydrogen Energy* **2020**, *46*, 23436–23462. [CrossRef]
2. Caglayan, D.G.; Weber, N.; Heinrichs, H.U.; Linßen, J.; Robinius, M.; Kukla, P.A.; Stolten, D. Technical potential of salt caverns for hydrogen storage in Europe. *Int. J. Hydrogen Energy* **2020**, *45*, 6793–6805. [CrossRef]
3. Miocic, J.; Heinemann, N.; Edlmann, K.; Scafidi, J.; Molaei, F.; Alcalde, J. Underground hydrogen storage: A review. *Geol. Soc. Lond. Spec. Publ.* **2023**, *528*, 73–86. [CrossRef]
4. 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]
5. Höök, M.; Söderbergh, B.; Jakobsson, K.; Aleklett, K. The Evolution of Giant Oil Field Production Behavior. *Nat. Resour. Res.* **2009**, *18*, 39–56. [CrossRef]
6. Sainz-Garcia, A.; Abarca, E.; Rubi, V.; Grandia, F. Assessment of feasible strategies for seasonal underground hydrogen storage in a saline aquifer. *Int. J. Hydrogen Energy* **2017**, *42*, 16657–16666. [CrossRef]
7. Lord, A.S.; Kobos, P.H.; Borns, D.J. Geologic storage of hydrogen: Scaling up to meet city transportation demands. *Int. J. Hydrogen Energy* **2014**, *39*, 15570–15582. [CrossRef]
8. Groenenberg, R.; Koornneef, J.; Sijm, J.; Janssen, G.; Morales-Espana, G.; van Stralen, J.; Hernandez-Serna, R.; Smekens, K.; Juez-Larré, J.; Goncalvez, C.; et al. Large-Scale Energy Storage in Salt Caverns and Depleted Gasfields. TNO (Executive Organization), EBN, Gasunie, Gasterra, NAM and Nouryon, Project Findings 060.36821, Subsidy Reference: TGEO118002, October 2020. Available online: https://publications.tno.nl/publication/34637700/8sBxDu/TNO-20 (accessed on 26 September 2023).
9. Jiang, D.; Fan, J.; Chen, J.; Li, L.; Cui, Y. A mechanism of fatigue in salt under discontinuous cycle loading. *Int. J. Rock Mech. Min. Sci.* **2016**, *86*, 255–260. [CrossRef]

10. Michalski, J.; Bünger, U.; Crotogino, F.; Donadei, S.; Schneider, G.-S.; Pregger, T.; Cao, K.-K.; Heide, D. Hydrogen generation by electrolysis and storage in salt caverns: Potentials, economics and systems aspects with regard to the German energy transition. *Int. J. Hydrogen Energy* **2017**, *42*, 13427–13443. [CrossRef]
11. Pan, B.; Yin, X.; Ju, Y.; Iglauer, S. Underground hydrogen storage: Influencing parameters and future outlook. *Adv. Colloid Interface Sci.* **2021**, *294*, 102473. [CrossRef]
12. Heinemann, N.; Booth, M.G.; Haszeldine, R.S.; Wilkinson, M.; Scafidi, J.; Edlmann, K. Hydrogen storage in porous geological formations—Onshore play opportunities in the midland valley (Scotland, UK). *Int. J. Hydrogen Energy* **2018**, *43*, 20861–20874. [CrossRef]
13. Lankof, L.; Tarkowski, R. Assessment of the potential for underground hydrogen storage in bedded salt formation. *Int. J. Hydrogen Energy* **2020**, *45*, 19479–19492. [CrossRef]
14. Tong, D.; Farnham, D.J.; Duan, L.; Zhang, Q.; Lewis, N.S.; Caldeira, K.; Davis, S.J. Geophysical constraints on the reliability of solar and wind power worldwide. *Nat. Commun.* **2021**, *12*, 6146. [CrossRef] [PubMed]
15. Deveci, M. Site selection for hydrogen underground storage using interval type-2 hesitant fuzzy sets. *Int. J. Hydrogen Energy* **2018**, *43*, 9353–9368. [CrossRef]
16. Lewandowska-Śmierzchalska, J.; Tarkowski, R.; Uliasz-Misiak, B. Screening and ranking framework for underground hydrogen storage site selection in Poland. *Int. J. Hydrogen Energy* **2018**, *43*, 4401–4414. [CrossRef]
17. 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]
18. Muhammed, N.S.; Haq, B.; Al Shehri, D.A.; Al-Ahmed, A.; Rahman, M.M.; Zaman, E.; Iglauer, S. Hydrogen storage in depleted gas reservoirs: A comprehensive review. *Fuel* **2023**, *337*, 127032. [CrossRef]
19. Zhang, J.; Li, Y.; Yin, Z.; Linga, P.; He, T.; Zheng, X.Y. Coupling amino acid L-Val with THF for superior hydrogen hydrate kinetics: Implication for hydrate-based hydrogen storage. *Chem. Eng. J.* **2023**, *467*, 143459. [CrossRef]
20. Chabab, S.; Théveneau, P.; Coquelet, C.; Corvisier, J.; Paricaud, P. Measurements and predictive models of high-pressure H2 solubility in brine (H_2O + NaCl) for underground hydrogen storage application. *Int. J. Hydrogen Energy* **2020**, *45*, 32206–32220. [CrossRef]
21. Luboń, K.; Tarkowski, R. Numerical simulation of hydrogen injection and withdrawal to and from a deep aquifer in NW Poland. *Int. J. Hydrogen Energy* **2019**, *45*, 2068–2083. [CrossRef]
22. Al-Yaseri, A.; Fatah, A.; Zeng, L.; Al-Ramadhan, A.; Sarmadivaleh, M.; Xie, Q. On hydrogen-cement reaction: Investigation on well integrity during underground hydrogen storage. *Int. J. Hydrogen Energy* **2023**, *48*, 35610–35623. [CrossRef]
23. Hagemann, B.; Rasoulzadeh, M.; Panfilov, M.; Ganzer, L.; Reitenbach, V. Hydrogenization of underground storage of natural gas. *Comput. Geosci.* **2016**, *20*, 595–606. [CrossRef]
24. Panfilov, M.; Gravier, G.; Fillacier, S. Underground Storage of H_2 and H_2-CO_2-CH_4 Mixtures. presented at the ECMOR X. In Proceedings of the 10th European Conference on the Mathematics of Oil Recovery, European Association of Geoscientists & Engineers, Amsterdam, The Netherlands, 4–7 September 2006. [CrossRef]
25. Choudhury, P.K.; Jena, R.; Tomar, S.K.; Puniya, A.K. Reducing Enteric Methanogenesis through Alternate Hydrogen Sinks in the Rumen. *Methane* **2022**, *1*, 320–341. [CrossRef]
26. Lovley, D.R.; Phillips, E.J.P. Competitive Mechanisms for Inhibition of Sulfate Reduction and Methane Production in the Zone of Ferric Iron Reduction in Sediments. *Appl. Environ. Microbiol.* **1987**, *53*, 2636–2641. [CrossRef] [PubMed]
27. Hagemann, B. *Numerical and Analytical Modeling of Gas Mixing and Bio-Reactive Transport during Underground Hydrogen Storage*; Cuvillier Verlag: Göttingen, Germany, 2017.
28. 2021 Annual Report: Tasks & Member Updates. IEA Hydrogen Technology Collaboration Program. 2021. Available online: https://www.ieahydrogen.org/annual-reports/ (accessed on 26 September 2023).
29. 2022 Annual Report: Tasks & Member Updates. IEA Hydrogen Technology Collaboration Program. 2022. Available online: https://www.ieahydrogen.org/annual-reports/ (accessed on 26 September 2023).
30. van Gessel, S.; Hajibeygi, H. Underground Hydrogen Storage: Technology Monitor Report. IEA Hydrogen Technology Collaboration Program Task 42. April 2023. Available online: https://www.ieahydrogen.org/task/task-42-underground-hydrogen-storage// (accessed on 26 September 2023).
31. Le Duigou, A.; Bader, A.-G.; Lanoix, J.-C.; Nadau, L. Relevance and costs of large scale underground hydrogen storage in France. *Int. J. Hydrogen Energy* **2017**, *42*, 22987–23003. [CrossRef]
32. International Energy Agency. Global Hydrogen Review 2022. IEA Publications. 2022. Available online: https://www.iea.org/reports/global-hydrogen-review-2022 (accessed on 26 September 2023).
33. Hychico. Available online: https://hychico.com.ar/esp/almacenamiento-subterraneo-hidrogeno.php (accessed on 26 September 2023).
34. Underground Sun Storage 2030. Available online: https://www.uss-2030.at/en/ (accessed on 26 September 2023).
35. Underground Sun Storage. Available online: https://www.underground-sun-storage.at/en/ (accessed on 26 September 2023).

36. RAG Austria AG, Axiom Angewandte Prozesstechnik GesmbH, Verbund AG, Montanuniversität Leoben, Universität für Bodenkultur Wien, and Energieinstitut an der Johannes Kepler Universität Linz, Underground Sun Storage Chemical Storage of Renewable Energy in Porous Subsurface Reservoirs with Exemplary Testbed. 840705. October 2017. Available online: https://www.underground-sun-storage.at/fileadmin/bilder/03_NEU_SUNSTORAGE/Downloads/Underground_Sun.Storage_Publizierbarer_Endbericht_English.pdf (accessed on 26 September 2023).
37. Konegger, H.; Loibner, A.; Waldmann, N.; Zaduryan, A.; Zeiser, M.; Rüdisüli, M.; Mutschler, R.; Sidler, D.; Boggiano, M.; Kunz, A.; et al. Final Report: Underground Sun Conversion—Flexible Storage. RAG Austria AG, Energie 360° AG, Vienna and Bern. May 2023. Available online: https://www.underground-sun-conversion.at/index.php?eID=dumpFile&t=f&f=17587&token=2fa4de16ca810b3014ea2880ae8aa37828f160ac (accessed on 26 September 2023).
38. Underground Sun Conversion. Available online: https://www.underground-sun-conversion.at/en/flexstore.html (accessed on 26 September 2023).
39. HyStorage | Uniper. Available online: https://www.uniper.energy/hystorage (accessed on 26 September 2023).
40. Escajadillo, E. Uniper Launches Research on German Hydrogen Storage Site. ICIS Explore. Available online: https://www.icis.com/explore/resources/news/2023/08/09/10913772/uniper-launches-research-on-german-hydrogen-storage-site (accessed on 26 September 2023).
41. Storage Data. Available online: https://www.fluxys.com/en/natural-gas-and-biomethane/products-services/ztp-storage-storage-data (accessed on 26 September 2023).
42. FLUXYS, Service Offer Description Storage Facility of Loenhout. July 2014. Available online: file:///Users/ernestoquintosfuentes/Downloads/Storage%2520Programme.pdf (accessed on 26 September 2023).
43. Belgium's Fluxys benefits from Europe's Rush to Secure Gas Supplies. Available online: https://www.euractiv.com/section/energy/news/belgiums-fluxys-benefits-from-europes-rush-to-secure-gas-supplies/ (accessed on 26 September 2023).
44. H. Project | April 2023, Hydrogen Underground Storage in Porous Reservoirs. ArcGIS StoryMaps. Available online: https://storymaps.arcgis.com/stories/2349ba3eb36d4473861b7701a08985e1 (accessed on 26 September 2023).
45. JAIC, Green Hydrogen Hub Denmark. Gas Infrastructure Europe. Available online: https://www.gie.eu/green-hydrogen-hub/ (accessed on 26 September 2023).
46. About GHH | Green Hydrogen Hub Denmark. Available online: https://greenhydrogenhub.dk/about-ghh/ (accessed on 26 September 2023).
47. Hydrogen Pilot Storage for Large Ecosystem Replication | HYPSTER Project | Fact Sheet | H2020′, CORDIS | European Commission. Available online: https://cordis.europa.eu/project/id/101006751 (accessed on 26 September 2023).
48. About the Project | HyPSTER. Available online: https://hypster-project.eu/about-the-project/ (accessed on 26 September 2023).
49. Netherlands Enterprise Agency (RVO), Embassy of the Kingdom of the Netherlands in France, and Netherlands Business Support Office Lyon & Nantes, Hydrogen in France, Developments and Opportunities for the Netherlands. Netherlands Enterprise Agency. March 2021. Available online: https://www.rvo.nl/sites/default/files/2022/01/Hydrogen-sector-study-France-maart-2021.pdf (accessed on 26 September 2023).
50. Storengy, GazelEnergie, Storengy and GazelEnergie Join Forces to Develop the Hydrogen Sector in the Moselle Department. 20 October 2020. Available online: https://www.storengy.com/sites/default/files/mediateque/pdf/2020-10/2020_10_20%2520Storengy%2520et%2520GazelEnergie%2520s%2527associent%2520pour%2520d%25C3%25A9velopper%2520la%2520fili%25C3%25A8re%2520hydrog%25C3%25A8ne%2520en%2520Moselle_EN.pdf (accessed on 26 September 2023).
51. JAIC, HyGreen Provence. Gas Infrastructure Europe. Available online: https://www.gie.eu/hygreen-provence/ (accessed on 27 September 2023).
52. HDF Energy and Teregéa, Communique de Presse Terega et HDF Energy. 7 July 2020. Available online: https://www.hdf-energy.com/site/assets/files/1209/communique_de_presse_terega_hdf_en_juillet2020.pdf (accessed on 26 September 2023).
53. S. E. GmbH, H2CAST Green Hydrogen Dtorage in Etzel. Available online: https://www.storag-etzel.de/en/storage/hydrogen-h2cast (accessed on 27 September 2023).
54. Garbe, A. About H2CAST Etzel. Available online: https://h2cast.com/project (accessed on 27 September 2023).
55. Future Projects. Available online: https://www.astora.de/en/company/astorah2/future-projects (accessed on 27 September 2023).
56. HPC Krummhörn | Uniper. Available online: https://www.uniper.energy/hydrogen-pilot-cavern (accessed on 27 September 2023).
57. Bailey, M. German Westküste 100 green hydrogen project secures funding. *Fuel Cells Bull.* **2020**, *2020*, 11. [CrossRef]
58. Project Description | Westkueste100.de. Available online: https://www.westkueste100.de/en/project-description/ (accessed on 27 September 2023).
59. JAIC, Bad Lauchstädt Energy Park. Gas Infrastructure Europe. Available online: https://www.gie.eu/bad-lauchstadt-energy-park/ (accessed on 27 September 2023).
60. Bad Lauchstädt Energy Park Now in Implementation Phase. Bad Lauchstädt Energy Park Now in Implementation Phase. Available online: https://www.uniper.energy/news/bad-lauchstaedt-energy-park-now-in-implementation-phase (accessed on 27 September 2023).
61. RWE, Hydrogen Project GET H2 Nukleus. Available online: https://www.rwe.com/en/research-and-development/hydrogen-projects/hydrogen-project-get-h2/ (accessed on 27 September 2023).

62. GET H_2 Nukleus. OGE. Available online: https://oge.net/en/hydrogen/our-hydrogen-projects/get-h2-nukleus (accessed on 27 September 2023).
63. The German National Hydrogen Council, Statement: Hydrogen Storage Roadmap 2030 for Germany from 4th November 2022. 4 November 2022. Available online: https://www.wasserstoffrat.de/fileadmin/wasserstoffrat/media/Dokumente/EN/2023/2022-11-04_NWR-Position-Paper_Hydrogen-Storage-Roadmap.pdf (accessed on 27 September 2023).
64. Blume, L. Hydrogen Cavern for Mobility—Wasserstoff-Niedersachsen.de. Hydrogen-Lower-Saxony.com. Available online: https://www.wasserstoff-niedersachsen.de/en/hydrogen-cavern-for-mobility/ (accessed on 28 September 2023).
65. Aquamarine. Available online: https://mfgt.hu/en/Akvamarin (accessed on 28 September 2023).
66. Tamás Mérő and Gáspár Geöczeöl, Ongoing Hydrogen Projects in Porous Reservoir in Hungary. Available online: https://www.software.slb.com/-/media/software-media-items/software/documents/external/technical-presentations/digital-forum-2022/et/10-hydrogen-projects-in-porous-reservoir-in-hungary--vision-ambition-and-realisation.pdf?la=en&hash=62D8F9543F2C24B9C8196C86ED0B38E1F971267B (accessed on 28 September 2023).
67. ESB and dCarbonX Launch Kinsale Head Hydrogen Storage Project. ESB Corporate. Available online: https://esb.ie/media-centre-news/press-releases/article/2021/08/12/esb-and-dcarbonx-launch-kinsale-head-hydrogen-storage-project (accessed on 28 September 2023).
68. Jerneja Sedlar, North Adriatic Cross-Border Hydrogen Valley (NAHV)–Lessons Learned (Till Now)). February 2023. Available online: https://www.clean-hydrogen.europa.eu/system/files/2023-03/2.%2520North%2520Adriatic%2520cross-border%2520Hydrogen%2520Valley%2520%2528NAHV%2529.pdf (accessed on 28 September 2023).
69. The Project. HyStock. Available online: https://www.hystock.nl/en/about-hystock/the-project (accessed on 28 September 2023).
70. Demonstration Hydrogen Storage A8, HyStock. Available online: https://www.hystock.nl/en/about-hystock/demonstration-hydrogen-storage-a8 (accessed on 28 September 2023).
71. Underground Gas Storage Facility Damasławek. Available online: http://www.gaz-system.pl/en/transmission-system/investment-projects/damaslawek-ugs.html (accessed on 28 September 2023).
72. de Saldanha, P.C.L.Q. Sines H_2 Hub: A Cost Perspective of the Transmission and Storage Infrastructure of the Sines Green Hydrogen Hub. Master Thesis, Delft University of Technology, Delft, The Netherlands, 2021. Available online: http://resolver.tudelft.nl/uuid:3d395140-7169-4e0f-8e75-ec3b2d8924dc (accessed on 28 September 2023).
73. Carneiro, J.F.; Matos, C.R.; Van Gessel, S. Opportunities for large-scale energy storage in geological formations in mainland Portugal. *Renew. Sustain. Energy Rev.* **2019**, *99*, 201–211. [CrossRef]
74. GreenH2Atlantic Project: Creation of Hydrogen Production Hub in Portugal. Available online: https://www.greenh2atlantic.com/project (accessed on 28 September 2023).
75. First Important Project of Common European Interest in Hydrogen Technology Approved by the European Commission Comes from NAFTA | Nafta Speicher. Available online: https://nafta-speicher.de/en/news/first-important-project-common-european-interest-hydrogen-technology-approved-european (accessed on 28 September 2023).
76. International Trade Administration U.S. Department of Commerce, Spain Renewable Hydrogen Roadmap. Available online: https://www.trade.gov/market-intelligence/spain-renewable-hydrogen-roadmap (accessed on 28 September 2023).
77. Hydrogen Storage. Hybrit. Available online: https://www.hybritdevelopment.se/en/a-fossil-free-development/hydrogen-storage/ (accessed on 28 September 2023).
78. Williams, J.D.O.; Williamson, J.; Parkes, D.; Evans, D.J.; Kirk, K.L.; Sunny, N.; Hough, E.; Vosper, H.; Akhurst, M.C. Does the United Kingdom have sufficient geological storage capacity to support a hydrogen economy? Estimating the salt cavern storage potential of bedded halite formations. *J. Energy Storage* **2022**, *53*, 105109. [CrossRef]
79. Al-Shafi, M.; Massarweh, O.; Abushaikha, A.S.; Bicer, Y. A review on underground gas storage systems: Natural gas, hydrogen and carbon sequestration. *Energy Rep.* **2023**, *9*, 6251–6266. [CrossRef]
80. ANGUS+—Helmholtz-Centre for Environmental Research. Available online: https://www.ufz.de/index.php?en=37525 (accessed on 28 September 2023).
81. Richard Stevenson, Alan Leadbetter, and Louis Day, Project HySecure Phase 1 Summary September 2019, Inovyn Enterprises Limited, Storengy. November 2019. Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/866376/Phase_1_-_Inovyn_-_HySecure.pdf (accessed on 28 September 2023).
82. Networks & Storage. Hydrogen UK. Available online: https://hydrogen-uk.org/the-hydrogen-story/storage/ (accessed on 28 September 2023).
83. Advanced Clean Energy Storage. Energy.gov. Available online: https://www.energy.gov/lpo/advanced-clean-energy-storage (accessed on 28 September 2023).
84. Hubs | ACES Delta. Available online: https://aces-delta.com/hubs/ (accessed on 28 September 2023).