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A Review on Large-Scale Underground Hydrogen Storage Technologies

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Abstract: Hydrogen, recognized as a clean and sustainable energy carrier, is gaining increasing attention due to its high energy density and low environmental impact. Underground hydrogen storage (UHS) offers a feasible solution to balance hydrogen supply and demand on a large scale. This review comprehensively summarizes the main characteristics of hydrogen under various PVT conditions, its environmental benefits, and the rationale for considering underground storage. Key factors influencing UHS, including geochemical and microbial reactions and storage integrity, are analyzed. The principles of UHS and the types of geological formations suitable for storage—such as salt caverns, aquifers, and depleted oil and gas reservoirs—are reviewed along with current domestic and international projects. Special focus is given to the technical challenges of using depleted reservoirs, including issues of leakage, trap and facility integrity, and hydrogen consumption via sulfide reactions. The paper concludes that China has strategic advantages in developing UHS due to abundant geological resources, technological innovation potential, and an integrated hydrogen industry chain, although it is still in the early stages of development.

Keywords: Underground hydrogen storage; salt caverns; depleted gas reservoirs; geochemical reactions; microbial processes; caprock integrity.

1. Introduction

Hydrogen has emerged as a promising energy carrier due to its high gravimetric energy density, potential for zero-emission energy systems, and versatility in various applications [1, 2]. However, the low volumetric energy density of hydrogen at ambient conditions, challenges associated with its storage and transport, as well as safety concerns related to leakage and embrittlement, present significant obstacles to its widespread adoption [2].

Research and applications of underground hydrogen storage have gained traction both domestically and internationally in recent years. In Europe, projects such as HyUnder in Germany have explored the feasibility of storing large volumes of hydrogen in porous geological formations, including salt caverns and aquifers [3]. In the United States, the National Renewable Energy Laboratory (NREL) has conducted pilot studies on depleted gas fields as potential storage sites [4]. In China, institutions such as the China University of Petroleum and Sinopec have initiated studies and pilot demonstrations focusing on depleted oil and gas reservoirs and underground aquifers [5].

Basic types of gas storage facilities include salt caverns, porous aquifers, and depleted hydrocarbon reservoirs. Each type presents distinct advantages and technical challenges in terms of reservoir geology, integrity, and operational costs [6]. The key factors influencing underground hydrogen storage encompass geochemical and microbial reactions that may consume hydrogen or compromise storage integrity, as well as technical difficulties related to reservoir permeability, caprock sealing, and wellbore integrity [5, 7].

2. Main Characteristics of Hydrogen

2.1. Physicochemical Properties of Hydrogen

Hydrogen exhibits a low molecular weight (2g/mol) and a correspondingly low density: approximately 0.0899 kg/m³ at standard temperature and pressure (STP, 0°C, 1 atm) [8]. When compressed to 200 bar, its density increases to approximately 16 kg/m³, while liquid hydrogen at −253°C achieves a density of about 70 kg/m³ [9]. In comparison, methane at STP has a density of 0.656 kg/m³, and compressed natural gas (CNG) at 200 bar reaches about 180 kg/m³ [9].

Table 1. Physical properties of hydrogen and methane

Property	Hydrogen (H_2)	Methane (CH_4)
Molecular weight (g/mol)	2.016	16.043
Density (kg/m³)	0.082	0.657
Viscosity (Pa·s)	0.89×10^{-5}	1.1×10^{-5}
Aqueous solubility (mol/kg)	7.9×10^{-4}	1.4×10^{-3}
Standard boiling point (°C)	−253	−165
Critical pressure (Pa)	1.30×10^{6}	4.63967×10^{6}
Critical temperature (°C)	−239.95	−82.3
Heating value (kJ/g)	120 – 142	50.2 – 55.5
Diffusivity in water (m²/s, 25 °C)	5.13×10^{-9}	1.85×10^{-9}

Gravimetric energy densities differ markedly: hydrogen's value is roughly 120 MJ/kg, compared to methane's 50 MJ/kg, but volumetric energy density for hydrogen is significantly lower than that of hydrocarbons [10, 11].

2.2. Environmentally Friendly Energy

Combustion of hydrogen produces water vapor as the primary byproduct, rendering it an environmentally friendly energy vector with negligible direct emissions of CO_2, SO_2, NOx, or particulate matter [12]. When produced via renewable pathways—such as electrolysis using solar or wind power—hydrogen becomes a truly low-carbon fuel [13]. However, if generated from fossil-based sources without carbon capture, hydrogen production can still lead to significant greenhouse gas emissions [14].

2.3. Industrial-scale Cost Analysis of Underground Hydrogen Storage

The cost of hydrogen storage is a critical component of the overall hydrogen supply chain. Conventional aboveground storage methods—high-pressure tanks or cryogenic vessels—incur high capital and operational expenses, as well as energy penalties for compression and liquefaction [15]. Underground storage, by contrast, offers the potential for lower per-unit storage costs due to large-scale buffering capacity, reduced land footprint, and insulation by the subsurface environment, which mitigates thermal losses [16]. Furthermore, underground reservoirs can leverage existing infrastructure and geological containment to provide safer, large-volume storage [17].

The industrial-scale application of underground hydrogen storage technology depends not only on the cost of the storage technology itself, but more critically on the reduction of electrolytic hydrogen production costs. Since electrolysis accounts for the dominant share of costs in the hydrogen production–storage value chain, lowering the cost of hydrogen production via electrolysis will be a decisive factor in enabling large-scale deployment of underground hydrogen storage.

3. Main Factors Affecting Underground Hydrogen Storage

3.1. Hydrogen-brine-rock geochemical reactions

Hydrogen can participate in geochemical reactions within the subsurface, such as reacting with minerals in reservoir rocks and with cement or steel well casings, potentially forming unwanted compounds like water or hydrogen sulfide [18]. Phyllosilicates and iron-bearing minerals present in porous sandstones can catalyze hydrogen oxidation, reducing the storage efficiency [19]. Additionally, hydrogen's small molecular size facilitates diffusion through microfractures, raising the risk of loss to overlying formations [20].

3.2. Microbial growth in the reservoir

Microbial activity in subsurface formations can lead to hydrogen consumption. Sulfate-reducing bacteria (SRB), for instance, utilize hydrogen to reduce sulfate to sulfide, producing H_2S, which can corrode steel components and pose safety hazards [21]. Other microbial communities, such as methanogens, may convert hydrogen into methane via CO_2 reduction, altering the gas composition and reducing stored hydrogen volume [22]. Factors such as temperature, pH, nutrient availability, and the presence of competing electron acceptors influence the rate of microbial consumption [23].

3.3. Geomechanical considerations for storage integrity

Cyclical hydrogen injection and reproduction leads to cyclical pressure changes on intact and fault rock behaviour, short and long-term chemical interaction of hydrogen on intact rock and faults, and stress–strain-sorption on mechanical and transport behaviour, all of which can have crucial impact on the storage integrity.

Maintaining reservoir and caprock integrity is paramount to prevent hydrogen leakage. Caprocks—typically low-permeability shales or evaporites—must exhibit hydraulic conductivities below 10^{-8} m/s to ensure containment [24]. Faults, fractures, or wellbore violations can compromise sealing, necessitating rigorous site characterization, monitoring, and remediation strategies [25]. Steel materials used in well casings must withstand hydrogen embrittlement, which can cause microcracks and structural failure.

4. Principles and Types of Underground Hydrogen Storage

4.1. Principles of Underground Hydrogen Storage

As shown in Figure 1, Underground hydrogen storage (UHS) entails injecting hydrogen gas into a subsurface formation under pressure and withdrawing it as needed. Key principles include ensuring that the reservoir's pore volume can accommodate hydrogen, maintaining differential pressure between injection and overlying formations to prevent upward migration, and preserving reservoir deliverability over cyclic injections. A cushion gas (often inert or non-commercial) may be left in place to maintain pressure and avoid reservoir collapse.

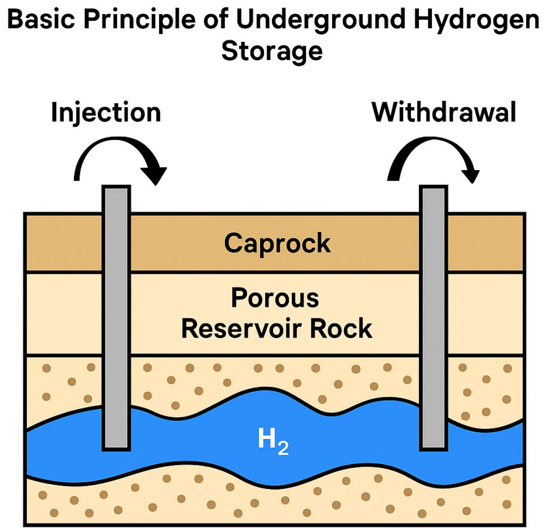

Figure 1. basic principle of UHS

4.2. Geological Feature Requirements

As shown in table2, Salt caverns—created by solution mining of halite deposits—are widely regarded as the most suitable geological formation for hydrogen storage due to their nearly impermeable nature, absence of microbial activity, and ability to self-heal minor fractures. Aquifer storage leverages porous, water-saturated sandstone formations with an impermeable caprock; however, it often requires maintaining a cushion gas and presents greater risks of geochemical dilution due to brine interactions. Depleted gas reservoirs offer the advantage of existing infrastructure—wells, pipelines, and compression facilities—and proven containment history, but challenges include residual hydrocarbon presence, potential reactivity, and the need to assess caprock integrity.

Table 2. Three Types of Underground Hydrogen Storage Reservoirs

Type	Geological Setting	Depth (m)	Operating Pressure (bar)	Storage Capacity	Working Gas Ratio (%)	Injection–Withdrawal Frequency	Typical Operational Mode
Salt Caverns	Salt-bearing sedimentary basins	300–1800	30–210	Large; proportional to cavern volume	>70	Up to 10 cycles per year	Suitable for high-frequency seasonal storage
Depleted Gas Reservoirs	Hydrocarbon-bearing sedimentary basins	300–2700	15–285	Large to very large; similar to natural gas reserves	5–60	1–2 cycles per year	Seasonal storage
Aquifers	All sedimentary basins	400–2300	30–315	Very large	20–50	1–2 cycles per year	Seasonal storage with potential gas losses

4.3. Domestic and International Project Examples; Current Research Status

Currently, four pure hydrogen storage facilities in salt caverns are in operation worldwide. In Texas, USA, three independent salt cavern hydrogen storage sites serve the petrochemical industry. In Europe, the only existing salt cavern hydrogen storage facility is located in Teesside, United Kingdom. It consists of three caverns with a total capacity exceeding 20,000 m^3. This facility has been operating for over 50 years, primarily supplying hydrogen for ammonia and methanol production.

In China, research at the Sheng li Oilfield has demonstrated successful cyclic hydrogen injection and withdrawal in a depleted gas reservoir, examining reservoir performance, geochemical interactions, and caprock sealing. Academic institutions such as the China University of Petroleum have conducted laboratory-scale experiments to evaluate hydrogen's interaction with sandstone cores under simulated reservoir conditions.

5. Depleted Oil and Gas Reservoir Hydrogen Storage Technology Status

5.1. Key Challenges: Flow Leakage, Caprock and Facility Integrity Failure, Sulfide Reaction Consuming Hydrogen

Depleted oil and gas reservoirs present several technical challenges when repurposed for hydrogen storage. Hydrogen's small molecular size and high diffusivity raise the likelihood of migration through microfractures or existing natural fractures, leading to potential flow leakage. Caprock sealing, which effectively contained methane for millions of years, may behave differently with hydrogen due to distinct fluid properties and pressure regimes.

Wellbore integrity is another concern: legacy casing and cement may not be designed to withstand hydrogen embrittlement, which can induce microcracks and compromise structural strength. Additionally, residual hydrocarbons and sulfur-bearing minerals can react with hydrogen, forming H_2S through abiotic or biotic processes, consuming part of the stored hydrogen and generating corrosive byproducts [21]

5.2. Research Directions for Underground Hydrogen Storage

Current research is focused on developing coatings and alloys for well casings that resist hydrogen embrittlement, as well as advanced cement formulations to maintain zonal isolation. Monitoring technologies—such as fiber-optic sensing for real-time leak detection and geochemical fingerprinting to assess hydrogen purity—are under active development.

Microbial control strategies include biocide injection and nutrient limitation to suppress sulfate-reducing and methanogenic activity. Reservoir simulation models have been refined to incorporate hydrogen-specific properties, dual-porosity effects, and coupled geochemical reactions to predict long-term storage performance. Hybrid storage concepts, such as blending hydrogen with natural gas to create 'hythane,' are also being explored to leverage existing infrastructure and mitigate reactivity risks.

6. Summary

Under in-situ stress conditions, elevated temperatures, pressures, and the presence of organic acids can enhance caprock sealing by promoting ductile behavior and self-healing of minor fractures. China's vast resource advantage—comprising numerous potential depleted and declining fields—provides ample opportunities to develop underground hydrogen storage sites. The complex geological conditions in many basins foster innovations in reservoir management, monitoring technologies, and integrity assurance.

Furthermore, the coordination between upstream and downstream segments of the hydrogen energy industry chain supports the development of integrated solutions, from hydrogen production and transport to underground storage and distribution. The broad market applications, including grid balancing, renewable energy buffering, and decarbonizing hard-to-abate sectors, underscore the potential scale advantage of underground hydrogen storage.

While China possesses favorable conditions and a solid foundation for industrial-scale deployment, domestic underground hydrogen storage remains at an early stage. Key hardware and software technologies—such as large-scale salt cavern construction, advanced wellbore materials, and comprehensive reservoir simulation platforms—have yet to coalesce into a mature, standardized development framework. Continued research, pilot demonstrations, and policy support are essential to realize the full potential of underground hydrogen storage in the next decade.

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