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Underground Hydrogen Storage: A Critical Review in the Context of Climate Change Mitigation

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Abstract

Review Article

Increasing population and anthropogenic activities are leading to a rise in global temperatures called global warming and climate change. To tackle this crisis, substantial efforts have been made such as renewable energy expansion and implementation of carbon capture and storage (CCS) projects. The Paris Agreement's goal is to limit the increase in global temperature and climate change mitigation strategies are adopted to achieve it. Decarbonization, negative emissions, and radiative forcing geoengineering are important technologies for this purpose because they decrease potential risks. Hydrogen has great potential in clean combustion and reduction of carbon emissions in different sectors like steel production. The cost trends indicate that green hydrogen could become a comparatively more efficient technology as compared to hydrogen generated from fossil fuels in the coming years. There is a need for hydrogen storage to support grid balancing and renewable energy systems. This study highlights the limitations and benefits of underground hydrogen storage mechanisms, including salt caverns, porous rock formations, and depleted hydrocarbon reservoirs. These are sustainable methods because they offer economic feasibility and large-scale storage, but it is important to consider geological suitability, hydrogen embrittlement, and environmental concerns. According to the literature, underground hydrogen storage is a better option than above-ground storage. The future outlook predicts that there will be increased investments in underground hydrogen storage technologies in the global transition to a greener energy paradigm.

Keywords: Global warming; Climate change mitigation; Renewable energy; Underground storage; Paris Agreement; Green hydrogen.

1. INTRODUCTION

1.1. Brief Overview of Climate Change and Mitigation Measures

Climate change is a shift in the patterns of climate mainly due to the emission of greenhouse gases from anthropogenic activities and natural systems. Climate change, propelled predominantly by anthropogenic activities, has become a focal global concern. Recent data highlights an alarming increase in global temperatures; the last five years (2018-2022) have been the warmest on record, with an average rise of 1.2°C in the global temperature above pre-industrial levels (Olatunde-Aiyedun, Olatunde, & Ogunode, 2022). Concurrently, erratic weather patterns have led to an 18% increase in extreme weather events over the past decade. As the CO_2 concentration in the atmosphere surpasses 415 ppm, a level unseen in the past 3 million years, the pressing urgency to mitigate this crisis becomes evident (Johansen, 2023; Ray, Giri, Ray, Dimri, & Rajeevan, 2021). In response, global renewable energy capacity has seen an impressive surge, growing by 60% in the past five years, while carbon capture and storage

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(CCS) projects have doubled in number, aiming to sequester approximately 40 million tons of CO_2 annually by 2025 (Kartal, Samour, Adebayo, & Depren, 2023; Pattanaik & Nayak, 2023). In 2018, 315 events due to natural disasters were reported that were mainly related to the climate. The change in climate affects all sectors such as water, food, ecosystem, health, infrastructure, and human habitat. Paris Agreement in 2015 took place to set goals of limiting global increase in temperature up to 2°C by 2100 and to pursue efforts to limit the increasing temperatures up to 1.5°C (Fawzy, Osman, Doran, & Rooney, 2020).

1.2 Climate Change Mitigation Strategies

1.2.1 Decarbonization technologies

It is a conventional method for mitigation that employs techniques to reduce the emissions of CO_2 such as efficiency gains, switching of fuel, renewable energy, nuclear power, the capture of carbon, its storage, and consumption. These methods are efficient because of their acceptable risk levels (Bustreo, Giuliani, Maggio, & Zollino, 2019).

1.2.2 Negative emissions technologies

The second technology captures and sequesters atmospheric CO_2 (Ricke, Millar, & MacMartin, 2017). The main methods include direct capture of carbon from the air and its storage, biochar, enhanced weathering, ocean fertilization, enhancement of ocean alkalinity, sequestration of carbon in the soil, afforestation, and reforestation, constructing wetlands, and their restoration. Alternative methods such as the use of negative emissions and techniques for storage like carbonation of minerals and the use of biomass in construction activities can be used (Pires, 2019).

1.2.3 Radiative forcing geoengineering technologies

The third method is applied to change the radiation balance of the earth by managing terrestrial and solar radiation. Its main purpose is to stabilize or reduce temperature. The temperature can be reduced without changing the concentration of greenhouse gases in the atmosphere. According to the literature, the main radiative forcing geoengineering methods are marine sky brightening, stratospheric aerosol injection, space-based mirrors, cirrus cloud thinning, different radiation management methods, and surface-based brightening techniques. There is a lot of risk involved in these methods because they are at an early stage or in the testing phase (Lockley, Mi, & Coffman, 2019).

1.2.4 Role of Hydrogen in Green Energy

Hydrogen, hailed as the 'fuel of the future', is progressively carving its niche in the green energy landscape (Rievaj, Gaňa, & Synák, 2019). Accounting for nearly 2% of the global energy mix in 2022, its average uptake has grown up to 10% over the past decade (De La Peña, Guo, Cao, Ni, & Zhang, 2022). Its clean combustion producing only water as a by-product when utilized in fuel cells stands in stark contrast to traditional fossil fuels, which emitted over 33 gigatons of CO_2 in the same year (Kühne, Bartsch, Tate, Higson, & Habet, 2022). Furthermore, as industries strive to reduce carbon footprints, hydrogen offers a promising pathway. For instance, in the steel industry, where carbon emissions reached approximately 2.6 gigatons in 2020, hydrogen-based reduction methods are projected to potentially decrease emissions by up to 30% by 2030, showcasing its pivotal role in transitioning sectors historically tethered to fossil fuels (Han *et al*., 2021; Vilchez & Jochem, 2020).

It is expected that hydrogen generation with fossil fuels will become more expensive due to its mitigation costs and carbon penalties. Almost 96% of hydrogen today is produced from SMR without CCS, (Mac Dowell *et al*., 2021) with a cost of around \$1.8 kg^{-1} (assuming 2020 prices of natural gas), with some blue hydrogen projects having a cost of \$2–3 kg^{-1} with CCS such as Quest in Canada. Hydrogen from green hydrogen is only 4% with a cost of \$3–\$6.66 kg^{-1} (Miocic *et al*., 2023).

Future scenarios of climate in Europe (Apostolou & Xydis, 2019) focus on hydrogen generation from solar and wind (green) and methane (natural gas steam reforming) and with CCS (blue). Cost trends suggest that green hydrogen will be more efficient as compared to hydrogen produced from natural gas in the next decade because the costs of other non-fossil energy sources such as solar, wind and hydro will decrease with an increase in their deployment. It is predicted that by 2030, the cost of green hydrogen production will be less than blue hydrogen in some locations (Cozzi *et al*., 2020). According to the International Energy Agency (IEA), with increased implementation or use of modern technology, there should be a \$1.3 kg^{-1} decrease in the costs of green hydrogen by 2030. In the event of a rise in the prices of natural gas, green hydrogen would be achieved much earlier.

1.2.5 Need for Hydrogen Storage

Hydrogen can support hydro-electrical power generation, solar, and wind (renewable energy) systems and the supply keeps on fluctuating because of changing weather patterns. For example, 300,000 MWh of renewable energy was restricted in California per month (Aniti, 2021). However, in August it faced rolling blackouts because there was no proper mechanism to store excess energy. The grid had a shortage of energy when there was a high demand. Balancing the grid daily increases emissions due to the consumption of fossil fuels. The hydrogen generation using excess renewable energy can help in direct distribution to the end-user and for balancing the grid.

Of all substances, Hydrogen has the lowest atomic mass (1.00784 u), low volumetric density, and highest gravimetric energy density (120 kJ g^{-1})

(Lemmon, 2010). Two ways are being considered to store hydrogen efficiently. The first one is to turn hydrogen into liquid chemicals and the second option is to use methanol or ammonia that can hold hydrogen directly and release it for energy purposes (Abdin *et al*., 2020). However, liquid hydrogen has high costs and is less suitable economically (Yin & Ju, 2020). Hydrogen gas is highly diffusive because of its properties. Hydrogen has a small size, less viscosity, low molecular weight, low density, and positive buoyancy over −251°C. Moreover, hydrogen is less soluble in water and the solubility increases with the increase in pressure. The properties of hydrogen at normal pressure and temperature are mentioned in Figure 1. (Chabab, Theveneau, Coquelet, Corvisier, & Paricaud, 2020).

1.2.6 Storage in porous rocks (saline aquifers and gas fields)

Coal is gasified to create town gas. Hydrogen was kept in saline aquifers during the town gas aquifer storage in the 1950s and 1970s. When steam and oxygen combine, a mixture of gas is created that contains 50%–60% hydrogen, 30% CH4, 20% CO2, and CO. In the Czech Republic (Lobodice), Germany (Engelborstel, Bad Lauchstaedt), and France (Beynes), town gas was stored in aquifers. There haven't been any reports of breakdowns or contamination from town gas storage areas for many years. However, various bio-geochemical processes in the storage reservoirs led to some modifications in the gas's chemical makeup (Tremosa, Jakobsen, & Le Gallo, 2023).

2. Sources of hydrogen

Hydrogen is produced from fossil fuels through steam methane (SMR), partial oxidation, auto thermal reformation (ATR), pyrolysis, or coal gasification, either with (around 1% of global production of hydrogen from fossil fuels) or without carbon capture and storage (CCS) and using water electrolysis (Nikolaidis & Poullikkas, 2017). There are other methods to produce low-carbon hydrogen such as microbes that use light to produce hydrogen from water (Akhlaghi & Najafpour-Darzi, 2020) biomass fermentation for hydrogen production (Łukajtis *et al*., 2018) biomass gasification or pyrolysis (Cao *et al*., 2020) photoelectrochemical reactions for splitting of water (Kumar & Himabindu, 2019) thermal and solar splitting of water (Safari & Dincer, 2020) using nuclear energy to carry out electrolysis and methane pyrolysis to create solid carbon and hydrogen.

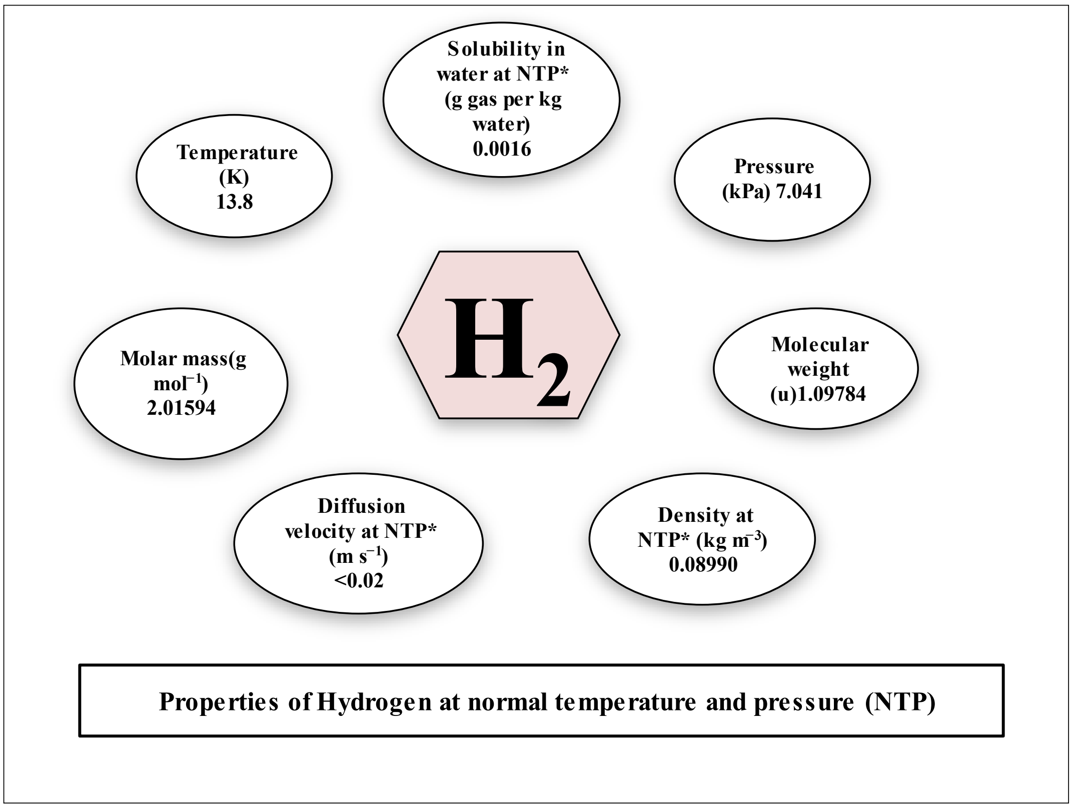

Fig 1: Different properties of Hydrogen (H_2) at Normal Temperature and pressure (NTP)

3. Underground Hydrogen Storage and its types

3.1 Salt Caverns

Salt caverns, naturally occurring or engineered, are substantial cavities within vast salt deposits, commonly created by injecting approximately 1,000 to 1,500 cubic meters of water per day to dissolve the salt (Abreu *et al*., 2023). Globally, there are currently over 500 operational salt caverns, primarily used for natural gas storage, with a combined volume of approximately 300 million cubic meters (Qiu, Lei, Wu, & Bi, 2021; Wang *et al*., 2020). Their intrinsic characteristics, like being virtually impermeable, render them an ideal environment for high-pressure hydrogen storage. Recent projects have demonstrated storage pressures reaching up to 200 bar, facilitating the storage of significant volumes of hydrogen within relatively small cavern footprints.

Table 1: Hydrogen Storage Costs (in $ per kilogram of hydrogen

Year	Salt Cavern Storage	Above-Ground Storage
2015	$2.50	$3.50
2016	$2.45	$3.40
2017	$2.40	$3.30
2018	$2.35	$3.20
2019	$2.30	$3.10
2020	$2.25	$3.00
2021	$2.20	$2.90

3.2 Porous Rock Formations

Specific sandstone and limestone layers are examples of porous rock formations, which are naturally occurring geological strata that include minute pores (Sambo *et al*., 2022). As of 2022, research indicated that over 2,000 suitable sites existed worldwide, with a combined potential storage volume exceeding 2 billion cubic meters (Schmitt, Rosa, & Daily, 2022). These sites typically reside at depths of 500 to 2,000 meters, ensuring the pressure is sufficient to keep hydrogen in a dense state (Sambo *et al*., 2022). The critical feature of these formations is the sealing mechanism: an overlying impermeable layer, often clay or shale, which prevents hydrogen from migrating upwards and ensures its long-term containment.

3.3 Depleted Hydrocarbon Reservoirs

Depleted hydrocarbon reservoirs, remnants of erstwhile oil or gas extraction endeavors, are increasingly being viewed as potential hydrogen storage facilities (Alms, Ahrens, Graf, & Nehler, 2023). With over 3,000 identified depleted reservoirs globally, their existing infrastructure, such as wells and pipelines, can be repurposed, potentially saving up to 30% in initial capital costs (Amirthan & Perera, 2023). However, they aren't devoid of challenges. Residual hydrocarbons can contaminate stored hydrogen, and their interaction can lead to unknown long-term effects. In 2021, a study revealed that approximately 5% of the stored hydrogen in such reservoirs might be lost to these residual hydrocarbons annually (Heinemann *et al*., 2021). This necessitates rigorous site assessments before conversions.

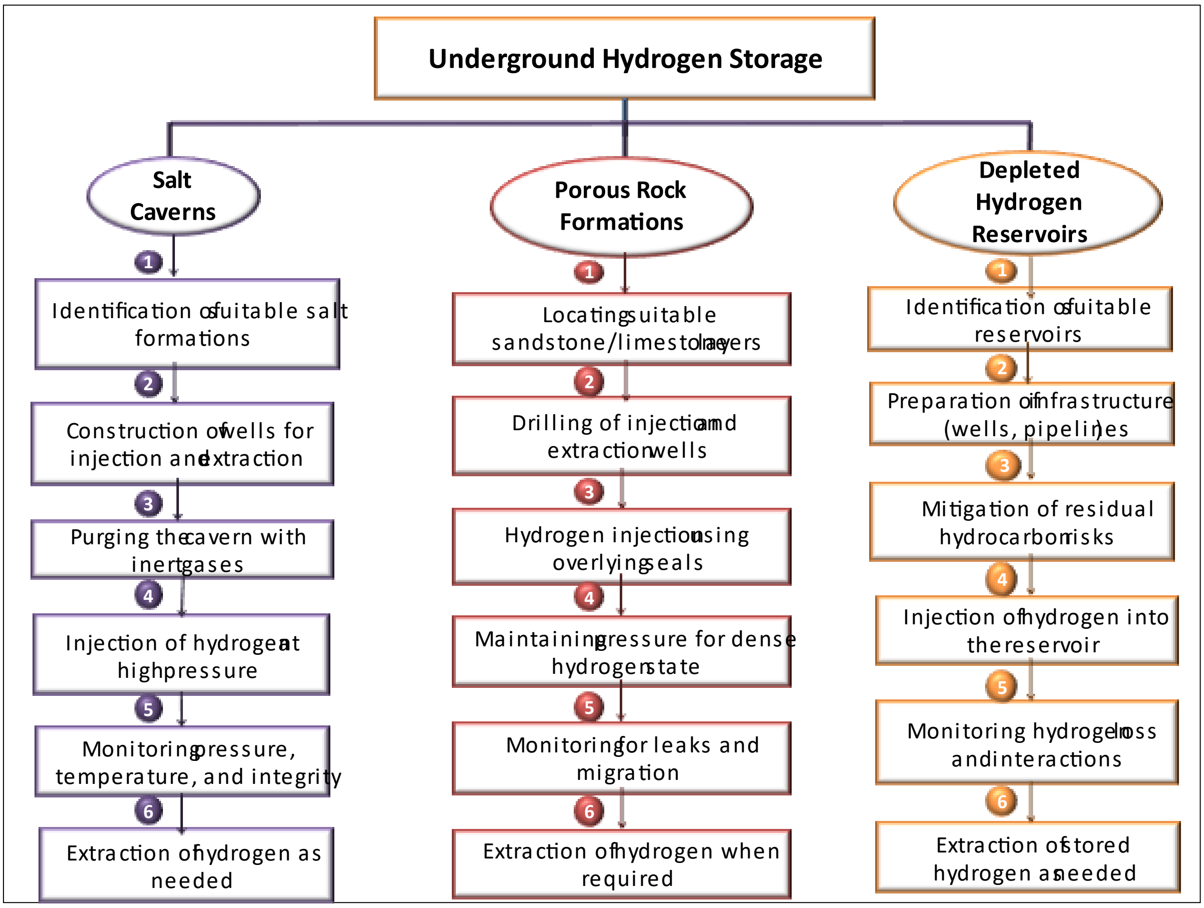

Fig 2: Flowchart Showing Underground Hydrogen Storage Mechanism

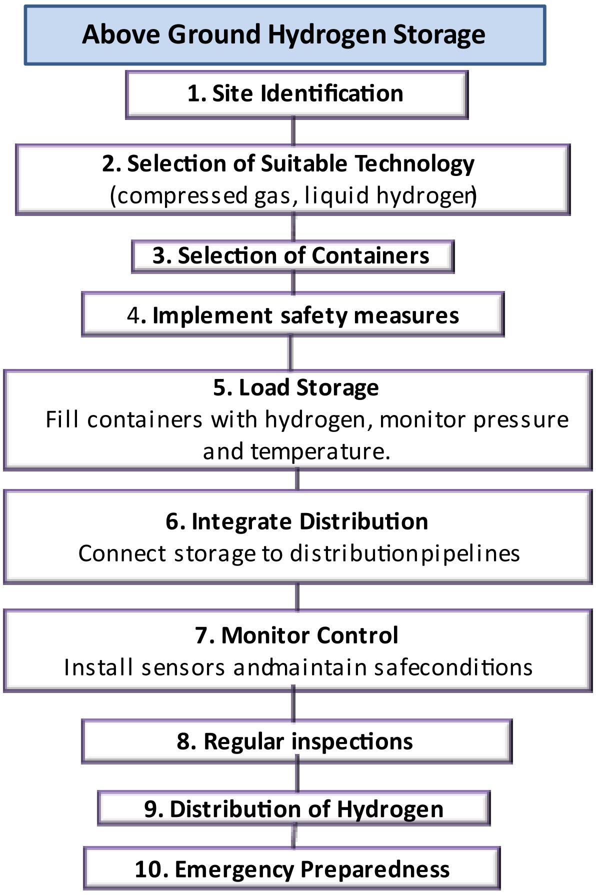

Fig 3: Flowchart Showing Aboveground Hydrogen Storage Mechanism

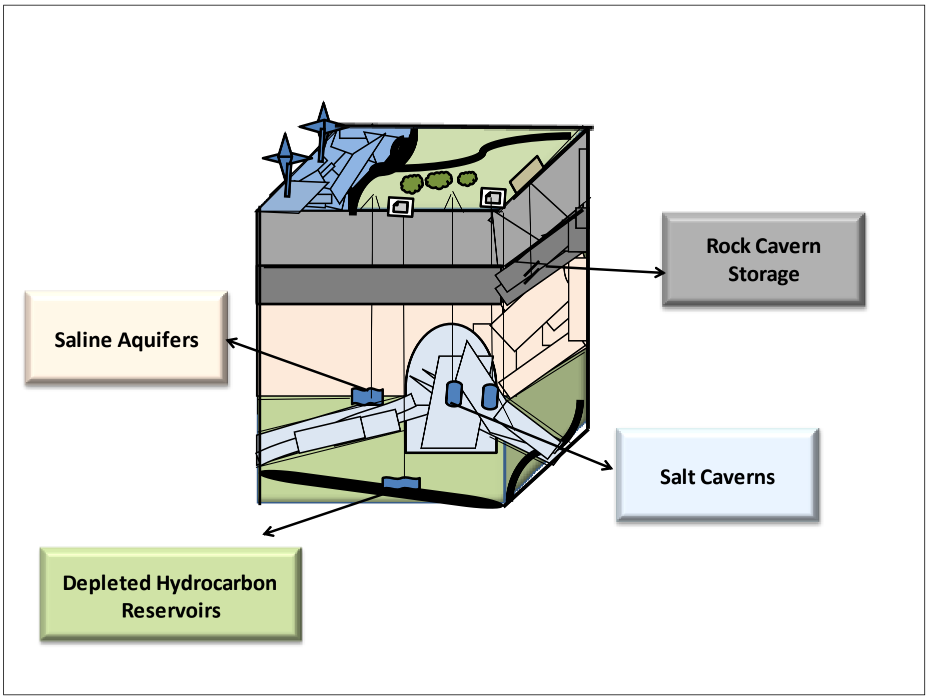

Figure 4: Types of Hydrogen Storage Mechanisms

4. Advantages of Underground Storage

Large-Scale Storage

Underground storage mechanisms offer unparalleled volumetric capacities for hydrogen storage (Buscheck *et al*., 2023). While an above-ground storage tank might hold up to 3,000 cubic meters of hydrogen, a medium-sized salt cavern can store a staggering 500,000 cubic meters (Fu, Zhou, & Zou, 2021; Papadias &

Ahluwalia, 2021). In 2022, the global underground hydrogen storage capacity was estimated at roughly 1.2 billion cubic meters, reflecting the capability to store nearly six months of global green hydrogen production (Muthukumar *et al*., 2023). Such vast storage volumes are critical in counteracting the seasonal variability of renewable energy sources. For instance, in regions like Northern Europe, where wind energy can vary by up to 60% between summer and winter, these underground reservoirs ensure a consistent hydrogen supply, bridging gaps between production highs and lows (Matos, Carneiro, & Silva, 2019).

Economic Feasibility

The sheer scale of underground storage introduces significant economic advantages. A 2021 study found that the cost of storing hydrogen in salt caverns ranged between $0.10 to $0.50 per kilogram of hydrogen, markedly lower than above-ground storage costs, which hovered between $1.00 to $2.00 per kilogram, factoring in land, materials, and maintenance (Alsaba, Al-Sobhi, & Qyyum, 2023; Tashie-Lewis & Nnabuife, 2021). This disparity becomes even more pronounced for long-term storage, where underground facilities have minimal operational costs compared to above-ground tanks which require regular inspections, maintenance, and potential replacements. Furthermore, in locations endowed with suitable geologies, the initial capital costs for creating underground storage, especially in depleted hydrocarbon reservoirs leveraging existing infrastructure can be up to 40% lower than setting up an equivalent above-ground facility (Shaw & Mukherjee, 2022; Yousefi, Groenenberg, Koornneef, Juez-Larré, & Shahi, 2023). This economic edge makes underground storage a compelling proposition for investors and policymakers alike.

Table 2: Costs of Hydrogen Storage Mechanisms

Criteria	Underground Storage	Above-ground Storage
Cost	- Potentially lower land acquisition costs - Lower costs in terms of insulation and thermal management due to constant temperature	- May be cheaper for small storage capacities, especially if using standard pressurized vessels
Long-term Storage	- Suitable for seasonal or long-term storage due to constant underground temperatures - Reduced evaporation or boil-off losses	- Suited for shorter-term storage due to potential boil-off issues
Initial Capital Cost	- May have higher initial cost because of excavation and ensuring structural stability	- Generally lower initial cost, particularly for small to medium installations
Maintenance	- Potentially less frequent maintenance due to reduced exposure to external elements - Monitoring for leaks might be more challenging	- Exposed to external conditions, so may require regular maintenance - Easier monitoring for leaks
Safety	- Reduced risk from natural disasters (e.g., tornadoes, hurricanes) - Natural containment in the event of a leak, limiting potential for explosive mixtures	- Potentially more vulnerable to external threats and natural disasters - In the event of a leak, there's a higher chance of explosive mixture with ambient air
Space Requirement	- Efficient land use since the majority of infrastructure is underground	- Requires more land or vertical space for tanks
Thermal Management	- Natural insulation due to the surrounding earth; constant temperature helps in reducing the boil-off	- Needs active thermal management systems to reduce boil-off and maintain the stored hydrogen at desired temperatures
Aesthetics	- Less visible infrastructure leading to less visual pollution	- Visible tanks and infrastructure may not blend with the surroundings
Environmental Impact	- Possible concern of disturbing underground ecosystems during excavation	- Smaller footprint might be less disruptive to surface ecosystems

Table 3: Comparison of the Capacity, Efficiency, Cost, and Geological requirements for Underground Hydrogen Storage Methods

Underground Storage Method	Capacity	Efficiency	Cost	Geological Requirements
Salt Caverns	500,000 m^3/cavern	95%	$0.10-$0.50/kg	Suitable salt deposits; depths >500m
Porous Rock Formations	1 million m^3/site	90%	$0.40-$1.20/kg	Permeable rock layers; impermeable seal above
Depleted Hydrocarbon Reservoirs	2 million m^3/reservoir	85%	$0.30-$0.90/kg	existing reservoirs; minimal hydrocarbon residue

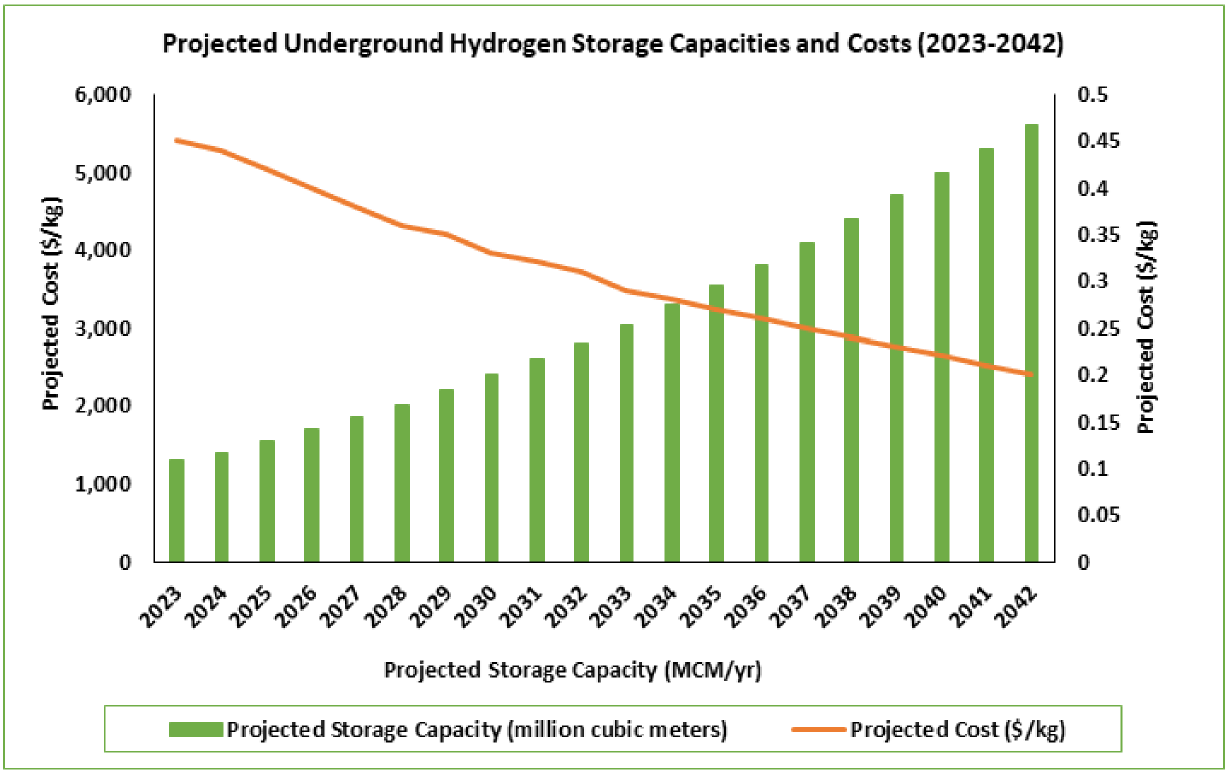

Figure 5: Projected Underground Hydrogen Storage Capacities and Costs (2023-2042)

A comprehensive review of the hydrogen value chain. Company profiles, technology analysis, key players, and hydrogen market forecasts.
By Chingis Idrissov, Dr Alex Holland and Dr Conor O'B

Historical Milestones and Current State of Technology

Salt caverns store compressed air, oil and natural gas (Zhang *et al*., 2017). Three salt caverns are operating in the USA and one is in the UK. Since the 1970s, they have been supplying hydrogen for the chemical industry. In the 1960's and 1970's, town gas consisting of 62% hydrogen was stored (Panfilov, 2016). Hydrogen can be stored for many decades in salt caverns and it can be recovered easily (Radoslaw Tarkowski, 2019).

New operations of hydrogen storage have been developed in the last decade in USA (ACES, Utah), UK (SSE thermal and Equinor, Aldbrough), France (HyGeo, Nouvelle-Aquitane and HyPSTER/Stopil_H2, Etrez), Netherlands (Gasunie, Veendam) and Germany (HYPOS, Bad Lauchstadt) (Le Duigou, Bader, Lanoix, & Nadau, 2017).

The potential of salt caverns has been analyzed in the last decade in different parts of the world. It is predicted that this technology will be a great option for the storage of hydrogen at a large scale (Radosław Tarkowski & Czapowski, 2018); (Caglayan *et al*., 2020).

Challenges and Limitations of Underground Storage

Geological Suitability:

The subsurface heterogeneity across the globe presents diverse challenges for underground hydrogen storage. As of 2023, only about 40% of global regions were identified to possess geologies suitable for salt caverns, porous rock formations, or repurposed hydrocarbon reservoirs (Chen *et al*., 2023; Krevor *et al*., 2023). In some areas, the absence of these formations altogether makes underground storage unfeasible. Furthermore, the feasibility studies required to validate these sites can be exhaustive and costly. A typical study, analyzing rock permeability, stability, and containment capability, can take up to two years and cost anywhere between $500,000 to $2 million, depending on the region and scale. There's also the latent risk of leakage or contamination. While advanced monitoring techniques have reduced leakage rates to less than 0.1% annually, even minor breaches can compromise the stored hydrogen's quality and pose environmental risks (Batterman, Grant-Alfieri, & Seo, 2023).

Hydrogen Embrittlement:

Hydrogen has a unique capability to infiltrate and deteriorate certain materials, a phenomenon termed 'hydrogen embrittlement' (Okonkwo *et al*., 2023). Geological formations with abundant metallic minerals are particularly vulnerable. For instance, formations with over 20% iron content can see up to a 15% reduction in their structural integrity over 10 years when exposed to hydrogen (Thiyagarajan, Emadi, Hussain, Patange, & Watson, 2022). This can not only reduce the storage site's lifespan but, in worst-case scenarios, lead to catastrophic failures, jeopardizing safety and causing significant financial setbacks. Current mitigation measures, like specialized linings, can reduce these effects but come with increased costs and maintenance requirements.

Environmental Concerns:

Beyond the immediate storage mechanics, the broader environmental implications of underground hydrogen storage are a significant area of concern. There's limited data on the long-term impact of hydrogen storage on groundwater quality, but initial studies from 2020 suggest a potential pH change in surrounding waters by ±0.5 units in proximity to storage sites. Similarly, shifts in soil microbiomes have been observed within a 500-meter radius, which could affect soil health and local agriculture. Furthermore, potential leakage, however minimal, could influence surrounding ecosystems, especially in areas with high biodiversity (Hiemstra & Spijker, 2017). Thus, while underground storage offers promising solutions, it necessitates a holistic environmental impact assessment to ensure sustainability in the long run.

5. Conclusion and Future Prospects

Comparative Advantage over Other Storage Methods

Underground hydrogen storage boasts distinctive advantages over its above-ground counterparts, especially in terms of storage density. In particular, salt caverns can achieve hydrogen storage densities of up to 200 kg/m^3, approximately three times the density achievable with above-ground tanks, which typically max out around 70 kg/m^3. This densification directly correlates with both cost and space efficiencies. For instance, storing 1,000 tons of hydrogen in salt caverns would require nearly 5,000 cubic meters, whereas above-ground tanks would necessitate almost 14,000 cubic meters, representing a potential 65% reduction in spatial requirements. Additionally, the subterranean nature of these storages acts as a natural containment barrier, minimizing the risk of catastrophic hydrogen releases. In the rare event of a leak, the hydrogen, being lighter than air, would naturally diffuse upwards and dissipate, thus ensuring an intrinsic safety level that's difficult to replicate with above-ground alternatives.

Policy Implications

The drive towards establishing underground hydrogen storage is not solely a technological endeavor but also a legislative one. Policymakers play an instrumental role in shaping the landscape of this technology. By the end of 2022, only 25% of countries with suitable geologies had comprehensive regulatory frameworks for underground hydrogen storage. These policies need to strike a balance, addressing environmental, safety, and community concerns, while also nurturing innovation and industry growth. For instance, setting stringent monitoring standards can ensure safety but also drive-up costs, potentially hindering investment. Conversely, overly lax regulations might expedite growth but at the expense of long-term sustainability and public trust. An effective policy will be one that harmoniously marries these facets, fostering a conducive environment for the development and deployment of underground storage solutions.

Future Outlook

The horizon looks promising for underground hydrogen storage. Projected investments in research and development for this domain are expected to surpass $500 million annually by 2030. This influx of capital and interest will likely spur advancements in materials science, enabling the development of linings and barriers that further enhance storage safety and efficiency. Monitoring technologies, leveraging IoT and AI, will become more sophisticated, potentially predicting and preventing issues before they manifest. Meanwhile, enhanced geological assessments using advanced seismic and sonar techniques could unlock previously unidentified storage sites. In essence, as the world gravitates towards a greener energy paradigm, the significance of underground hydrogen storage, fortified by continuous technological advancements, will undeniably remain pivotal in the energy transition narrative.

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Author Contributions

All authors equally participated in this work. Qudrat Ullah, Muhammad Qasim, Aneela Ulfat, and Arooj Fatima papered the first draft of this manuscript, Syeda Midhat Zahra, Aneela Ulfat, Sadaf Kyannai, and Syed Abidullah, modified, added, and reviewed the whole Manuscript and the corresponding author of this paper improve and add some suggestion.

Data availability: No data were used in this research work.

Declaration of Interests: The authors said they had no competing interests.

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Consent for Publication

All authors want to acknowledge and publish this work, in a reported prosperous journal, and all of our authors agreed to submit and publish this work in any related journal.

List of Abbreviations

CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
Ppm	Parts Per Million
IEA	International Energy Agency
SMR	Steam Methane Reforming
NTP	Normal Temperature & Pressure

MWh…………Megawatt-Hours
ACES…….......Advanced Clean Energy Storage

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