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Citation for published version:
Masoudi, M, Hassanpouryouzband, A, Hellevang, H & Haszeldine, RS 2024, 'Lined rock caverns: A hydrogen storage solution', *Journal of Energy Storage*, vol. 84, 110927.
https://doi.org/10.1016/j.est.2024.110927

Digital Object Identifier (DOI):
10.1016/j.est.2024.110927

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Journal of Energy Storage

Journal of Energy Storage 84 (2024) 110927

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Review Article

Lined rock caverns: A hydrogen storage solution

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ARTICLE INFO

Keywords:
Lined Rock Cavern
Geological Hydrogen Storage
Subsurface Energy Storage
Hydrogen Storage
Rock Cavern's Lining System

ABSTRACT

The inherent intermittency of renewable energy sources frequently leads to variable power outputs, challenging the reliability of our power supply. An evolving approach to mitigate these inconsistencies is the conversion of excess energy into hydrogen. Yet, the pursuit of safe and efficient hydrogen storage methods endures. In this perspective paper, we conduct a comprehensive evaluation of the potential of lined rock caverns (LRCs) for hydrogen storage. We provide a detailed exploration of all system components and their associated challenges. While LRCs have demonstrated effectiveness in storing various materials, their suitability for hydrogen storage remains a largely uncharted territory. Drawing from empirical data and practical applications, we delineate the unique challenges entailed in employing LRCs for hydrogen storage. Additionally, we identify promising avenues for advancement and underscore crucial research directions to unlock the full potential of LRCs in hydrogen storage applications. The foundational infrastructure and associated risks of large-scale hydrogen storage within LRCs necessitate thorough examination. This work not only highlights challenges but also prospects, with the aim of accelerating the realization of this innovative storage technology on a practical, field-scale level.

1. Introduction (why LRC?)

The rapid advancements in global development and the ensuing increase in energy demands emphasize the urgent need for robust and sustainable energy solutions. Although hydrocarbons have historically been the predominant sources of energy, the pressing need to address climate change compels a shift towards more sustainable, alternative energy carriers. Electricity, a significant energy medium, grapples with challenges related to storage efficiency and the susceptibility of infrastructure, more so with the growing dependency on renewable energy sources like wind and solar power. The inconsistencies in renewable energy generation, due to fluctuating weather conditions, highlight an acute need for advanced energy storage solutions [1–7]. The limitations of current electricity grids prevent us from producing significantly more or less energy than immediate demands, as doing so could strain the grid's stability. Combatting climate change fundamentally relies on addressing the pivotal issue of large-scale, reliable energy storage. To match the reliability of hydrocarbon and coal-based energy sources, effective energy storage and on-demand release are imperative. Hydrogen, with its high energy density, provides a promising alternative [8–15]. Excess energy, generated during periods of low demand, can be used to produce hydrogen, enabling efficient and scalable energy storage [16–19].

A spectrum of repositories, depicted in Fig. 1, is viable for hydrogen storage. Surface storage options, such as storing hydrogen in its liquid state at sub-zero temperatures, have limited capacity and high costs and are more suitable for small-scale energy storage with short charging and discharging times [20–22]. As the production of renewable energy continues to rise, there is a growing need for large-scale hydrogen storage solutions. Underground hydrogen storage within diverse geological structures and engineered repositories (as depicted in Fig. 1) offers promising alternatives [10,11,23]. As shown in Fig. 2, geological repositories uniquely provide energy storage capacities on the order of terawatt-hours (TWh). Deep geological formations like depleted hydrocarbon reservoirs, aquifers, and solution-mined salt caverns provide the potential for storing substantial volumes of gaseous hydrogen

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Abbreviations: LRC, Lined Rock Cavern; SMES, Superconducting Magnetic Energy Storage; CAES, Compressed Air Energy Storage; PHS, Pumped Hydro Storage; MIE, Minimum Ignition Energy; LPG, Liquefied Petroleum Gas; LNG, Liquefied Natural Gas; LCOS, Levelized Cost of Storage.

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https://doi.org/10.1016/j.est.2024.110927
Received 22 December 2023; Received in revised form 8 February 2024; Accepted 10 February 2024

[8,24,25]. However, these options are limited by the availability of suitable geological formations [26,27]. To expand the number of potential storage sites and enhance supply security, shallower options such as lined rock caverns can be considered. Although they offer lower capacity compared to deep geological formations (see Fig. 2), exploring these diverse storage options enables the development of a robust and flexible hydrogen storage infrastructure to support the integration of renewable energy sources into the energy grid. It is important to acknowledge that achieving a net-zero society will require a diversified portfolio of storage options encompassing various discharge times and capacities, as represented in Fig. 2. These different storage options will be indispensable in our pursuit of a sustainable future.

A lined rock cavern (LRC) is an excavated subterranean chamber in hard rock formations sealed with a special lining system to create a secure storage space. In LRCs, the surrounding rock mass handle the pressure and the lining system provides a barrier to prevent gas leakage and maintain the structural integrity of the cavern [31–34]. LRCs present an attractive option for hydrogen storage, offering several notable advantages [7,26,33–38].

Primarily, LRCs demonstrate a high degree of flexibility in terms of location, as they can accommodate a wide range of geological requirements. This versatility widens the scope of potential locations for hydrogen storage, particularly in areas where other storage options are limited by geological factors (e.g., regions with predominant igneous or metamorphic rocks). This flexibility allows for the installation of extensive hydrogen storage infrastructures in strategic vicinities such as near industrial clusters, power generation plants, major airports, renewable energy hubs, and import/export stations. This strategic positioning enhances the feasibility of utilizing hydrogen in comprehensive decarbonization strategies.

Furthermore, the lining system employed in LRCs ensures enhanced containment, mitigating the risk of gas leakage and bolstering overall safety protocols. The incorporation of the lining facilitates higher pressure levels, resulting in increased gas storage capacity. Additionally, LRCs exhibit substantial structural stability, facilitating efficient injection and withdrawal of hydrogen gas, thereby ensuring high deliverability within short notices, i.e., an ideal candidate for peak load cycling. The capability of LRCs to operate at lower pressures minimizes the need for cushion gas, optimizing storage capacity. Moreover, LRCs are well-suited for multiple annual cycles and extended storage periods. Crucially, the stored gas in LRCs remains isolated from formation fluid (brine or hydrocarbon) and formation rock, averting any necessity for subsequent gas purification or drying processes, and thus mitigating biogeochemical interactions and hydrogen loss, and thereby eliminating the post-processing costs.

Evaluated from health, safety, and environmental standpoints, LRCs exert minimal impact, as they make use of existing rock formations, thereby reducing land use and the impact on landscape and aligning with sustainability goals. Furthermore, the controlled construction of LRCs allows for precise engineering and customization to accommodate specific storage requisites.

Underground hydrogen storage (within LRCs) is often regarded as a safer and more socially palatable solution in comparison to its surface counterparts, attributed to various factors. Primarily, hydrogen has a lower minimum ignition energy (MIE) compared to other fuels. MIE of hydrogen in air is approximately 17 μJ, whereas other flammable gases such as methane, ethane, and propane have MIE values ranging from 260 to 300 μJ [39]. Low MIE coupled with high flammability range predispose hydrogen to form explosive mixtures with air. Thus, it becomes imperative to mitigate ignition sources in proximity to hydrogen storage zones, emphasizing the importance of such subterranean storage solutions in reducing associated risks and reinforcing safety and public

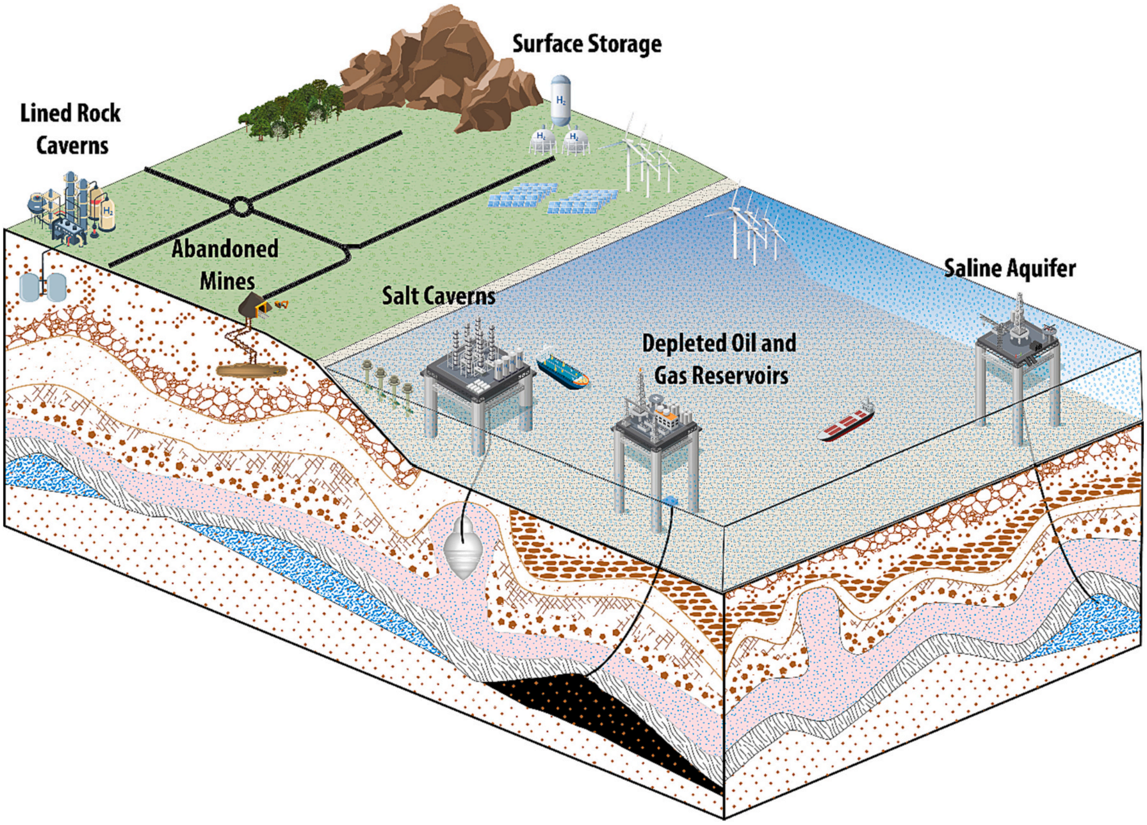

Fig. 1. A schematic representation of diverse geological and surface repositories for hydrogen storage. The illustration encompasses Lined Rock Caverns, Abandoned Mines, Salt Caverns, Depleted Oil and Gas Reservoirs, and Saline Aquifers. Additionally, surface storage facilities are depicted, showcasing the breadth of options available for accommodating the increasing demand for hydrogen storage infrastructure.

acceptability. Due to the ease of access during construction, Lined Rock Caverns (LRCs) offer significant advantages for sensor installation, making the monitoring process considerably more efficient compared to salt caverns and other geological storage alternatives such as depleted hydrocarbon reservoirs and aquifers.

Separation of the underground facilities from the atmosphere provides a high level of safety and security. Hydrogen storage solutions, whether housing the element in a compressed or liquefied state, necessitate high operational pressures. Any malfunctions in storage vessels or instances of over-pressurization can result in ruptures, causing sudden hydrogen release and posing potential hazards. Additionally, surface storage facilities can be susceptible to natural disasters, such as earthquakes, floods, typhoons, or fires, which can compromise the integrity of storage infrastructure and potentially cause leaks or ruptures. It is worth mentioning that rock caverns can also be prone to damage from seismic activity. However, when strategically placed at a distance from faults, they can constitute a secure choice for storage facilities. As an example, the 2011 Great East Japan Earthquake triggered a devastating tsunami that inflicted extensive damage on the above-ground facilities of the Kuji Underground Oil Stockpile Base in Iwate Prefecture, while the underground storage remained unscathed [40]. Beyond natural disasters, during times of conflict or war, surface storage facilities can become focal points for sabotage or attacks, escalating the associated risk spectrum. The insulation provided by underground storage in such scenarios further underscores the enhanced security and resilience offered by such arrangements.

This study presents a comprehensive evaluation of the potential of lined rock caverns for hydrogen storage, highlighting the unique challenges and promising avenues for advancement. By addressing the uncharted territory of using LRCs for hydrogen storage, the work aims to accelerate the practical implementation of this innovative storage technology at a large-scale level.

2. LRC components

Lined rock caverns are typically located in host rocks that do not possess sufficient tightness to store liquids or gases at elevated pressures. This limitation is even observed in rocks with low permeability, where mechanical stress can induce fractures or faults. Nevertheless, various methods can be to seal the rock and create suitable conditions for storage of high-pressure gas or liquid. Sealing in rock caverns can be achieved through two main approaches: groundwater control (using natural ground water and water curtains) and permeability control (lining, freezing, grouting, or ensuring tight rock) to prevent fluid ingress and movement [18,41]. In this study, our focus is on lined rock caverns. LRCs typically encompassing several components: the host rock, a lining system, access shafts and tunnels, and surface facilities as demonstrated in Fig. 3. This comprehensive arrangement serves as a representation of an integrated, sustainable hydrogen storage solution, harmonizing advanced engineering practices with strategic geological placement.

2.1. *Rock mass*

The rock mass is pivotal in the engineering of lined gas storage caverns because it serves as a structural bulwark that supports the pressure exerted by the stored gas on the cavern lining. As a result, the thickness of the steel lining does not need to be as substantial as that of surface storage tanks. The cavern's depth must surpass a critical threshold to ensure that the resisting overburden pressure (weight of the overlying rock mass) is greater than the maximum gas pressure. Otherwise, the rock mass may uplift and fail [32,34,42]. Determining the optimal depth and location for a LRC involves comprehensive site investigations and contemplation of several factors, including uplift safety, rock mass properties (such as initial stress conditions, modulus, and compressive and tensile strength, geometry of joint sets, stress-strain behavior), desired storage capacity and gas pressure, excavation costs, and environmental impact.

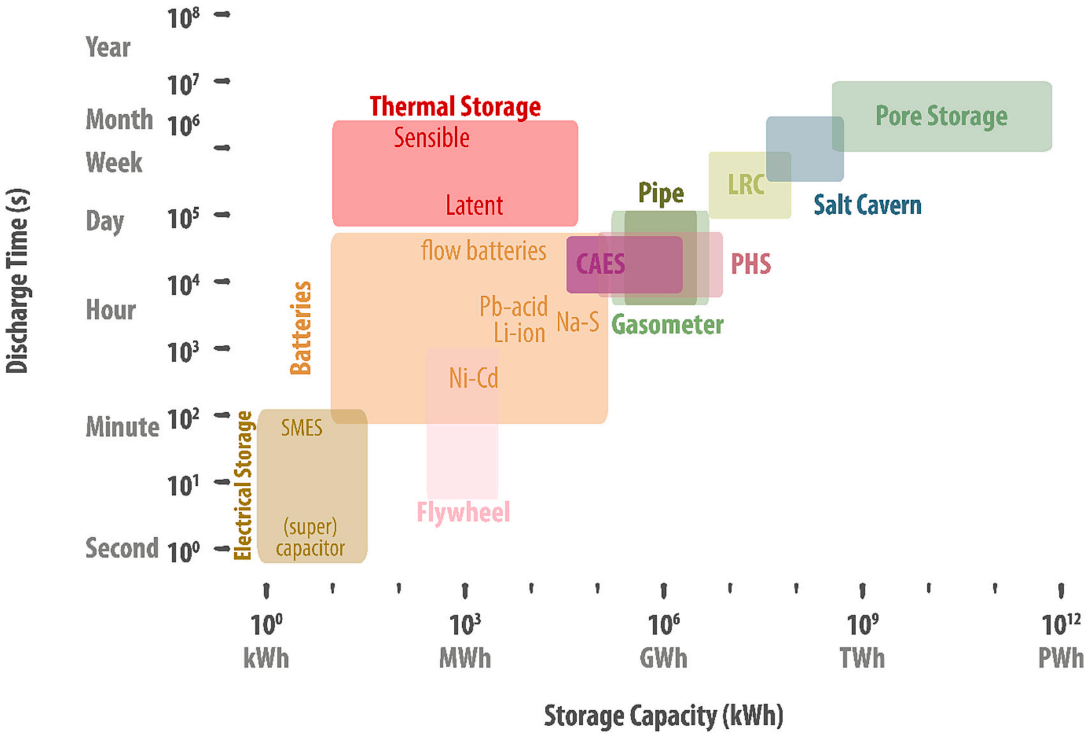

Fig. 2. Comparison of energy storage capacity vs discharge time of different renewable energy storage solutions. Both axes employ logarithmic scales. Data sourced from references [28–30]. Storage capacities for hydrogen-related solutions were computed using [11]. SMES = Superconducting Magnetic Energy Storage, CAES = Compressed Air Energy Storage, PHS = Pumped Hydro Storage, and Pore Storage = Porous media storage in depleted hydrocarbon fields and saline aquifers.

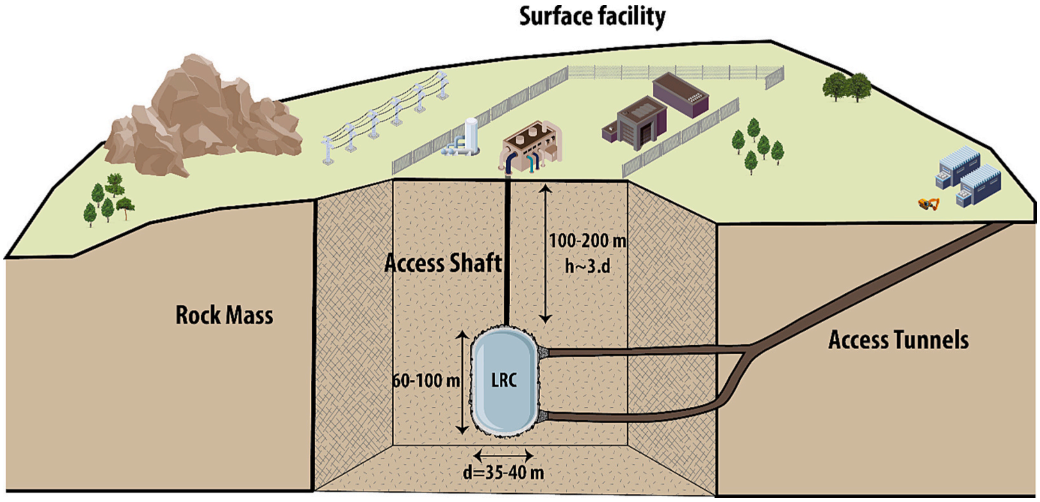

Fig. 3. The essential components of a LRC system designed for hydrogen storage. An LRC, ensconced within solid rock mass, is structured as a vertical cylinder. Access tunnels provide secure ingress for maintenance and monitoring, along with crucial surface facilities designed for the meticulous management and oversight of the stored hydrogen.

To gain insights into the response of rock mass to high-pressure fluctuations, it is imperative to conduct integrated scaled-down experimental and modeling investigations [43–45], as well as additional modeling studies at different scales [33,46–48]. In the given context, the utilization of large-scale models is considered a conventional approach in investigating the repercussions of significant perturbations, such as excavation and operational activities involving cyclical pressure fluctuations, on the mechanical behavior of the rock mass. These models are employed to analyze various aspects such as crack distribution, as well as elastic and plastic deformation of rock mass. Conversely, smaller scale models are employed to scrutinize the response of the lining and the interaction between its components in the presence of localized heterogeneities within the rock mass, including the opening of the rock joints due to the elevated gas pressure inside the cavern [32,35,38]. These numerical or analytical models are further utilized in conjunction with reliability and risk analysis tools to ensure the safety of LRC operations. They provide a detailed understanding of various failure modes and associated factors, as elaborated in references [32, 34, 42, 47–49]. These works provide in-depth explanations of these subjects and various failure modes.

As illustrated in Fig. 3, LRCs are designed in the shape of a vertical cylinder, typically spanning 100 m in height and 40 m in diameter. To

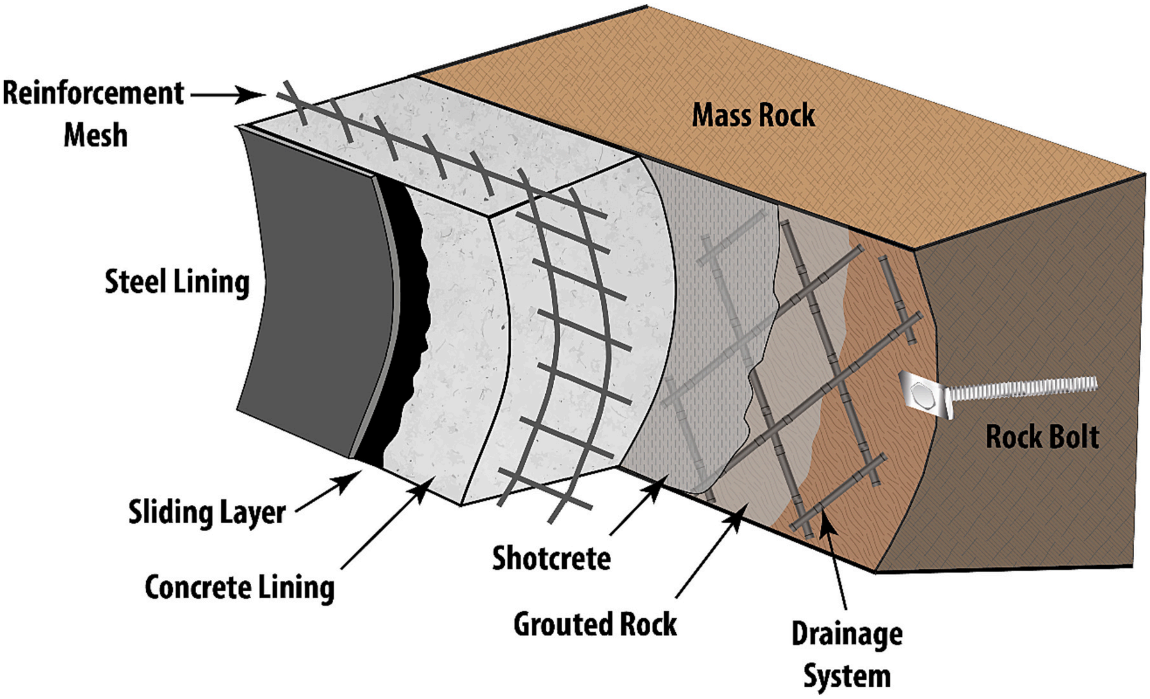

Fig. 4. Lining system – a detailed cross-sectional representation of a rock cavern's lining system. This comprehensive design illustrates the multi-layered protective strategy employed for hydrogen storage. Key features include a robust steel lining to ensure gas tightness, a sliding layer to reduce friction between the concrete lining and the steel lining, a concrete lining to transfer gas loads to the surrounding rock mass, a reinforcement mesh to enhance the tangential strength of the concrete lining, shotcrete and grouting for stabilizing the rock mass, and a strategically positioned drainage system to manage groundwater flow and the placement of monitoring sensors. Rock bolts further secure the entire assembly to the surrounding rock mass.

ensure effective pressure balancing, LRCs are optimally positioned at a depth between 100 and 200 m, usually three times the diameter of the cavern [32–35,38,50]. The ecological footprint of LRC construction can be reduced by repurposing waste rocks for other applications, such as road construction, land reclamation or buildings [34].

2.2. *Lining system*

The lining system plays a crucial role in LRC as it ensures structural integrity, gas containment, and environmental safeguarding. The specific design, composition, and materials employed in the lining components may vary depending on project specifications and local regulations. However, a typical lining configuration, as illustrated in Fig. 4, is commonly utilized [32,35,38].

2.2.1. *Drainage system*

A typical drainage system in LRCs involves the installation of perforated PVC pipes with diameters ranging from 100 to 200 mm. These pipes are positioned beneath the mesh reinforcement along the rock wall, following a rhombic pattern with a spacing of 1–2 m. The mesh reinforcement is securely fastened to the wall and then covered with a protective layer of permeable shotcrete.

The drainage system serves a dual purpose. Firstly, it manages the flow of groundwater through the perforated pipes, mitigating hydrostatic pressure on the lining during construction, inspections, repairs, or periods of inactivity, and safeguarding against water influx during concrete placement. Secondly, the drainage system serves as an integral component of the safety and monitoring system, enabling the detection, localization, and collection of any gas leaks [32,34,38,51]. Gas evacuation measures in case of leakage involve the utilization of two ring-shaped horizontal gas collector pipes, which are situated at both the top and bottom of the wall. Furthermore, to facilitate effective gas flow, multiple larger gas evacuation pipes are also employed. These evacuation pipes ensure that any escaping gas is efficiently directed from the horizontal collector pipes towards the ground surface.

The incorporation of the drainage system is designed to exert minimal influence on the LRC's mechanical behavior [48]. However, it is essential to assess the local mechanical behavior of the concrete lining in the proximity of the drainage pipes. A relevant example of such analysis can be found in the section 5.3.2 of Johansson's work [32]. The investigation revealed that the calculated crack widths with drainage pipes are comparable to the results obtained without drainage pipes.

This circulation of water in the drainage system can lead to the formation of deposits that can clog the pipes. Therefore, to prevent (bio) geochemical clogging and avoid lowering the groundwater table, it is recommended to keep the drainage system closed during the operation of the LRC, unless a leakage is detected [32].

An alternative method for instituting the drainage system is using a sand layer between the concrete wall and the rock mass. The sand layer serves as a diffusion medium for rock cracks, dissipating them across a limited area on the concrete surface and preventing undisturbed propagation of cracks through the concrete. However, the continuous sand layer is not particularly effective for localizing leaks [52].

2.2.2. *Shotcrete*

Shotcrete, also known as sprayed concrete, serves various essential functions in LRCs. Primarily, it provides structural support and reinforcement during both construction and operation phases. Shotcrete, along with permanent anchors and rock bolts, plays a critical role in maintaining the stability of the cavern walls, preventing rock blocks from falling and potential collapse. It is imperative for shotcrete to adhere firmly to the rock surface and withstand the loads exerted by loose blocks. Additionally, shotcrete helps reduce groundwater inflow into the cavern during excavation, ensuring a controlled environment. Moreover, shotcrete enhances the hydraulic contact with the drainage system, facilitating effective water management within the cavern. Furthermore, shotcrete acts as a protective layer for the drainage systems by shielding the drainage pipes during the process of filling the space between the steel lining and the rock with concrete. This protective layer minimizes the interaction and interlocking between the rock surface and the concrete lining, enhancing the overall integrity and durability of the system. By smoothing out the initial roughness resulting from excavation, shotcrete also provides suitable surface for the subsequent lining installation [32,38,48,53].

2.2.3. *Concrete lining*

The concrete layer is a key component of LRCs. It acts as an intermediate load transferring layer between the steel lining and the rock. Its primary function is to transmit the gas pressure in the cavern to the surrounding rock mass. It also helps to distribute the pressure evenly across the rock, which helps to prevent localized damage. Moreover, the concrete layer provides a smooth surface for the efficient installation of the gas-tight steel liner. When selecting the concrete quality, it is essential to consider factors such as compressive strength to ensure it can withstand the gas pressures without deteriorating [32,34,38].

The concrete layer is pivotal for strain reduction on the steel lining. As gas fills the cavern, it creates both perpendicular compressive and tangential tensile forces that lead to the opening and shearing of existing rock joints, causing deformation (Fig. 5). The compressive loads are transferred and supported by the rock mass. The localized tangential strains on the other hand, may result in cracks in the concrete lining and inducing tangential strain in the steel lining. Such stress and strain can be managed by:

(1) Incorporating reinforcement in the concrete layer to hold it together and strengthen the tensile strength.
(2) Incorporating a sliding layer to adjust the friction coefficient between the steel and concrete for a better distribution of cracks and reducing localized strain and preventing stress concentrations.
(3) Using suitable additives in the concrete to improve its cracking behavior.

However, it is important to acknowledge that it is impossible to prevent concrete cracking due to the general expansion of the cavern. Thus, a thorough examination of the general cracking behavior of the concrete lining is essential, considering cavern pressure, subsequent rock joint opening, and the possibility of induced fractures. This should also involve contemplation of the evolution of pressure, temperature, and stress over the operational life of the cavern [32,35,42,47,48,54,55]. An illustrative example of such analysis can be found in the work of Damasceno et al. (2023) [48]. In their study, they modeled the lining response and the interactions between its various components to elevated gas pressure. They conducted finite element simulations to investigate the sequential behavior of rock joint opening resulting from tangential strains, cracking behavior of the concrete layer caused by the opening of rock joints, and the subsequent response of lining components.

It is recommended that the concrete layer is poured into the space between the rock and steel liner after the steel lining has been installed. This sequencing allows for the construction of the steel lining, which requires space for assembly, welding, erecting, and testing the steel lining or installing the reinforcement. In some projects, self-compacting concrete has been used to minimize the concrete thickness and to eliminate the need for vibrating pokers to achieve a uniform distribution. Water is often filled inside the steel tank to counterbalance the concrete pressure during pouring [32,35].

The reported concrete lining thickness for the large pilot projects falls within the range of 0.7 to 1 m (Table 1). However, it is important to note that the concrete lining thickness should be optimized, and it is subject to various considerations. Firstly, practical needs dictate a minimum thickness to allow for construction tasks such as constructing

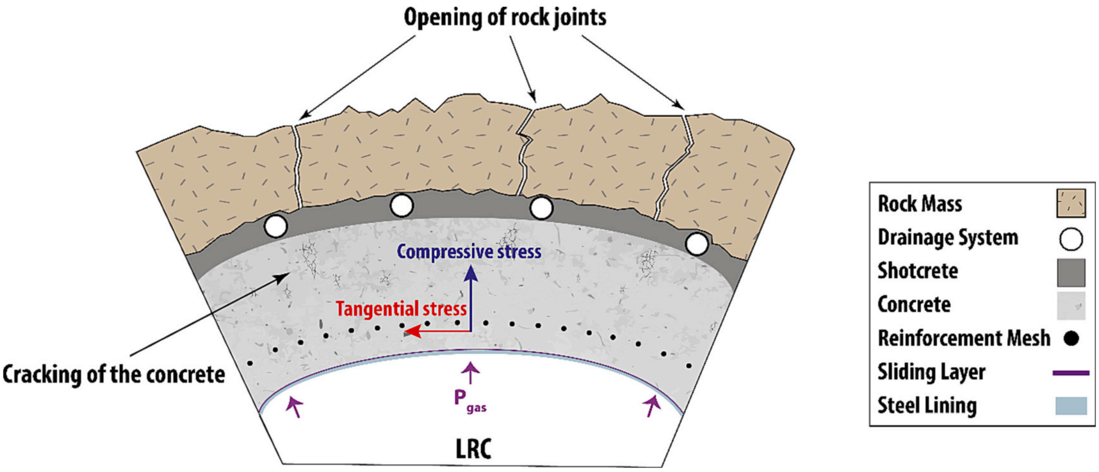

Fig. 5. Gas pressure creates perpendicular compressive and tangential tensile forces that lead to the opening and shearing of existing rock joints, causing deformation. The compressive loads are transferred and supported by the rock mass. The localized tangential strains on the other hand, may result in cracks in the concrete lining and inducing tangential strain in the steel lining.

the steel lining (welding and testing), installation of the steel reinforcement mesh, and pouring the concrete. Secondly, it must facilitate crack distribution and accommodate reinforcement. Lastly, it should provide adequate load-bearing support for drainage pipes mounted on the rock surface [32].

2.2.4. *Steel reinforcement mesh*

It is a steel mesh that is employed to enhance the (tangential) strength of the concrete lining. Its primary function is to ensure uniform distribution of deformations, thereby enabling potential cracks to be fragmented into smaller, narrower ones. This fragmentation reduces the impact of the cracks on the steel lining. To achieve a more balanced distribution of cracks, it is preferable to position the reinforcement mesh closer to the steel lining, where the tangential stress is the largest [32,35]. In the Skallen demonstration project, the reported value for the reinforcement diameter is 16 mm [31–33].

2.2.5. *Sliding layer*

The sliding layer is a thin layer (1–6 mm) of material such as bitumen or asphalt, placed on the entire outer surface of the steel lining. Its primary purpose is to reduce friction between the concrete lining and the steel lining, ensuring minimal shear resistance and facilitating relative movement between the two layers. By decreasing friction, the sliding layer helps distribute tangential strain caused by concrete cracking more evenly along the steel lining. Without any friction, stress in the steel lining would be uniformly distributed and proportional to the tangential strain, while high friction can lead to concentrated stresses at crack locations. In addition, the sliding layer provides corrosion protection and seals the concrete surface to prevent small gas leaks. It is important to consider factors such as material durability, temperature variations, mechanical properties, aging, shear resistance, deformability, and adhesion when selecting the appropriate material for the sliding layer [32].

2.2.6. *Steel lining*

The steel lining is composed of welded steel plates, forming a sturdy and durable enclosure that ensures gas tightness. It also serves as a structural framework for concrete casting. The steel lining can be fabricated as a complete unit or in sections. One approach is to construct it in stages, such as starting with the bottom cupola, followed by the top cupola, and then completing the cylindrical part. Another option is to begin with the bottom cupola and subsequently add the remaining sections [31,32].

Given the repeated cycles of filling and emptying the storage facility, it is essential to prioritize the mechanical integrity, fatigue resistance, and material selection of the steel lining. This is necessary to withstand the effects of hydrogen gas and any potential impurities it might contain, as well as to endure exposure to the external environment. From a structural perspective, it is essential to note that the primary load-bearing responsibility is not assigned to the steel lining. However, the lining must be capable of enduring the cyclic stress and strain. Potential failure of the steel lining can arise from various factors, including rupture due to significant deformations in the rock mass, leakage caused by low cycle fatigue, hydrogen embrittlement, and local failures stemming from weaknesses in the rock, concrete, welds, or corrosion. In the context of hydrogen storage, assuming satisfactory rock mass properties and minimal human error, cyclic fatigue and hydrogen embrittlement are identified as the primary threats to the steel lining. Controlling the maximum strain within the lining is vital to prevent fatigue failure. It is crucial to ensure that the fatigue load, comprising the strain range and the number of cycles, remains below the fatigue capacity to maintain the long-term safety and reliability of the steel lining. Furthermore, addressing the potential issue of hydrogen embrittlement is of utmost importance. Hydrogen gas has the potential to induce brittleness in the steel, leading to cracking and possible failure of the lining. Therefore, careful consideration and thorough testing of both the steel material and welds are necessary to select an appropriate steel type capable of withstanding hydrogen embrittlement [32,34,35,38]. It is worth mentioning that other materials such as epoxy resins have also been suggested as a substitution of stainless-steel for lining material [56]. As evident from Table 1, the thickness of the steel lining varies across different projects. Reported values are up to 20 mm.

2.2.7. *Monitoring system*

Establishing a proficient monitoring system is crucial to ensure the safety and performance of hydrogen gas storage facilities. The system should monitor multiple parameters, including pressure, temperature, leaks, structural integrity, and environmental conditions. By integrating a variety of sensors throughout the facility, such as the drainage system, concrete liner, surrounding rocks, and steel liner, comprehensive real-time monitoring data can be obtained. These sensors encompass a range of monitoring capabilities, including measuring pressure (piezometers), temperature (thermistors), deformation (extensometers), gas detection (explosimeters), joint movement (joint meters), incline measurements (inclinometers), strain levels (strainmeters), reinforcement status (reinforcement meters), and humidity levels (humidity sensors) [32,57–59].

Table 1
Experiences of gas storage in rock caverns.

Project	Stored gas	Date	Depth	Cavern shape and size	Leakage control methode	Geology	Condition	Comments	Ref.
Leyden coal mine, Denver, Colorado, USA	Natural gas	1961-2000	240-260	70.8 Mm^3 of gas @ 1.72 MPaG	Overlying impermeable claystone and an underlying aquifer		1.72 MPaG	Provided gas two or three times a year during high demand in winter, 5.8 e6 m^3 maximum withdrawal capacity	[26,86,97,98]
Anderlues coal mine, Belgium	Natural gas	Tests 1976, commercial use 1980	600 to 1100	6 to 10 Mm^3 (180 Mm^3 or 130,000 tons of CH_4)	A thrust fault at 600 m depth acts as a primary hydrogeological barrier/50 m thickness overburden		Maximum 0.35 MPa	- Max withdrawal rate 18 Mm^3/y - Ceased in 2000 due to the high costs of maintenance at the sealed shafts	[85,86]
Péronnes, Hainaut Coalfield, Southern Belgium	Methane	1978	60-1070	120 Mm^3 of CH_4 (85 000 tons).	Overburden between 32 and 100 m			Ceased in 1996 due to high local taxes	[85,86]
CAES pilot in former coal mine, Hokkaido, Japan	Compressed air	1990	450	57 m long tunnel, 6 m diameter.	Butyl synthetic rubber inside a 0.7 m of concrete	Coal	8 MPa	Daily air leakage of 0.2% was reported but it was below acceptable limits	[54,91]
KIGAM[a] LNG, Daejeon Science Complex, South Korea	Liquid Nitrogen (LN_2)	Constructed in 2003/operated in 2004	108	2 caverns with the size of 3.5 *3.5 * 10 = 110 m^3	- One cavern with steel plates (6-mm) with 300 mm of concrete/another cavern with butyl rubber sheets with 500 mm of concrete - Insulation panel thickness is 300 mm foam are sandwiched between plywood sheets	Limestone	−196°C	A pilot of CAES with the maximum pressure of 5Mpa has also been reported according to [58,95,96]	[93,94]
ANGAS[b] project, Kamioka mine, Japan	Compressed air	2004 to 2007	400	6 m in diameter, 10.5 m in length and about 240 m^3 in volume	Steel liner: less than 20 mm and 700 mm concrete	Sedimentary rock (sandstone and mudstone)	Max 20 MPa		[92]
CAES in Pingjiang PSH[c]	Compressed air		110	Horizontal cylinder, with 5 m length and 2.9 m	2.0-cm-thick fiber-reinforced plastic (FRP)	Granite	Max 10 MPa	Air mass leakage ratio of 3.2% at the highest pressure	[57]

plant, Hunan, China				diameter and volume of 28.8 m^3					
Grängesberg Research Plant, Sweden	Natural gas	Constructed in 1988/operated in 1989-1993	50	3 test rooms vertical cylinders 5 m in diameter and 10 m high	Room 1: 0.4 mm thick lining of austenitic stainless steel (SS2343) and concrete lining is about 0.4 m (reinforced) Room 2: 6 mm plates of micro-alloyed steel (SS 2134) with a sliding layer of asphalt. concrete lining of 0.6 m thick and unreinforced. Room 3: 0.5 mm thick lining of stainless steel with no sliding layer. The concrete lining is 0.3 m thick and conventionally reinforced.	Granite	(1) Limited cycles, 14 MPa (2) 200 cycles, max 52 MPa (3) 91 cycles, 28 MPa	- The tested concept proved to effectively contain the gas under challenging load conditions. - High-pressure leakage tests have demonstrated that even in the event of a substantial liner failure, it can be managed without significant adverse outcomes. - The plastic linear planned originally for room 3 failed during construction.	[32,99]
Skallen demonstration project, Halmstad, Sweden	Natural gas	2004	115	Vertical cylinder 52 m high and 36 m in diameter 40,000 m^3 rock cavern	- Ductile carbon steel with a thickness of about 12 mm - Sliding layer: 6 mm of polymer-modified bitumen with heavy geotextile reinforcement - Concrete lining thickness of about 1 m	Crystalline gneiss	Up to 20 MPa (including some tests at 52 MPa)	- Injection 20 days - Withdrawal 10 days - 1 km access tunnel with cross-sectional area of 28 m^2 and 1:7 slope gradient downwards - 90-meter shaft with a 1-meter diameter	[31–33]

[a] Korea Institute of Geoscience and Mineral Resources.
[b] Advanced Natural GAs Storage.
[c] Pumped storage hydropower.

2.2.8. Bolting and anchors

During the excavation of the access tunnels or the cavern, the necessity for either temporary or permanent rock support may arise, particularly in critical zones such as tunnel junctions, pump pits, or sections with poor rock mass quality. Bolting and anchoring will be used to achieve this. These measures ensure the stability of the rock mass by providing reinforcement and support, preventing collapses, and maintaining the structural integrity of the cavern [33–35].

2.3. Surface facility, shaft, and tunnel

This section covers the surface facility, shaft, and tunnel components of LRCs. Fig. 3 provides a visual representation of these three crucial elements. To facilitate excavation operations and the construction of the lining system within LRCs, a network of tunnels is employed to provide access. These access tunnels are designed to accommodate smooth logistical operations, allowing for the transportation of personnel, heavy machinery, equipment, and excavated rock. They are engineered to be sufficiently wide and appropriately sloped to support these activities effectively.

Vertical shafts serve as vital connections between the above-ground facilities and the cavern itself. Within these shafts, pipelines for the injection and withdrawal of gas are installed. The sealing of both the vertical shaft and access tunnels represents a complex aspect of the project and requires careful consideration, with specific measures in place to ensure the integrity of the system. The Skallen Demo project involved the establishment of a 1-km access tunnel, featuring a 28-square-meter cross-sectional area, descending with a 1:7 gradient. Additionally, a 90-m shaft with a 1-m diameter was constructed for the project [33].

The above-surface facilities associated with LRCs mirror those used in salt caverns. These facilities house essential control and process equipment, including compressor stations, heating/cooling systems, piping networks, valves, and metering devices. Additionally, comprehensive monitoring and safety systems are integrated to oversee and safeguard the entire operation.

3. Behavior of hydrogen gas

As previously stated, a distinctive advantage of utilizing LRC for hydrogen storage is that the hydrogen is only in direct contact with a non-reactive steel lining. Unlike depleted gas reservoirs and aquifers, there are no additional fluids or rocks present in the system. This eliminates the risk of hydrogen loss due to mixing or biogeochemical reactions and the need for studying complex multiphase flow in porous media. Consequently, pure hydrogen can be stored and released in LRCs without the need for additional drying or purification processes. Hence, in this section, our focus will be specifically on the behavior of pure hydrogen gas. A comprehensive examination of the thermodynamic and transport properties of hydrogen mixtures can be found in other sources [60,61].

Hydrogen storage in LRC is associated with frequent storing and releasing cycles. It means that hydrogen gas experience regular variation in pressure, influencing the inherent properties of hydrogen and dictating the possible gas storage and withdrawal rates [62]. Consequently, understanding the unique characteristics of pure hydrogen gas is essential for accurately predicting its performance and ensuring the safe and efficient operation of hydrogen storage systems in LRCs. Since most of the experiences for gas storage in LRCs come from natural gas, in this section, we have provided a comprehensive summary of the physiochemical properties of hydrogen in comparison to methane, as a representative of natural gas. Fig. 6 has been included to offer a concise overview and comparative analysis of the fundamental properties of hydrogen and methane. The side-by-side presentation allows for a clear understanding of the differences in molecular weight, density, viscosity, diffusion coefficients, energy values, ignition parameters, and flammability limits between the two gases. These insights are essential for comprehending their behavior, ensuring safety, and facilitating their application in energy storage and usage scenarios. All the properties are reported at normal atmospheric pressure and/or temperature (1 atm and 20 °C). The explanation of the terms outlined in Fig. 6 can be found in Supporting information.

Hydrogen gas, H_2, with a molecular weight of 2.016, is the lightest and smallest molecular gas, which grants it high diffusivity and buoyancy comparing to natural gas. Although these attributes enable H_2 to disperse rapidly in open environments, reducing the risk of flammability, they also increase the risk of leakage. At standard atmospheric conditions, H_2 is about eight times less dense than methane, exhibiting a colorless, odorless, tasteless, non-toxic, but flammable nature over a broad range of concentrations in air.

To gain a comprehensive understanding of hydrogen gas, including its pressure and temperature within the cavern, precise modeling tools must be employed. One can utilize computational fluid dynamics (CFD) models, combined with thermodynamic models (such as distinct equations of states [60,63]) to achieve accurate results. CFD models excel in simulating fluid flow dynamics, while thermodynamic models, employing equations of state, accurately represent hydrogen's physical properties under different conditions, offering insights into its behavior within storage environments.

In a notable study by Damasceno [42], hydrogen gas was observed to

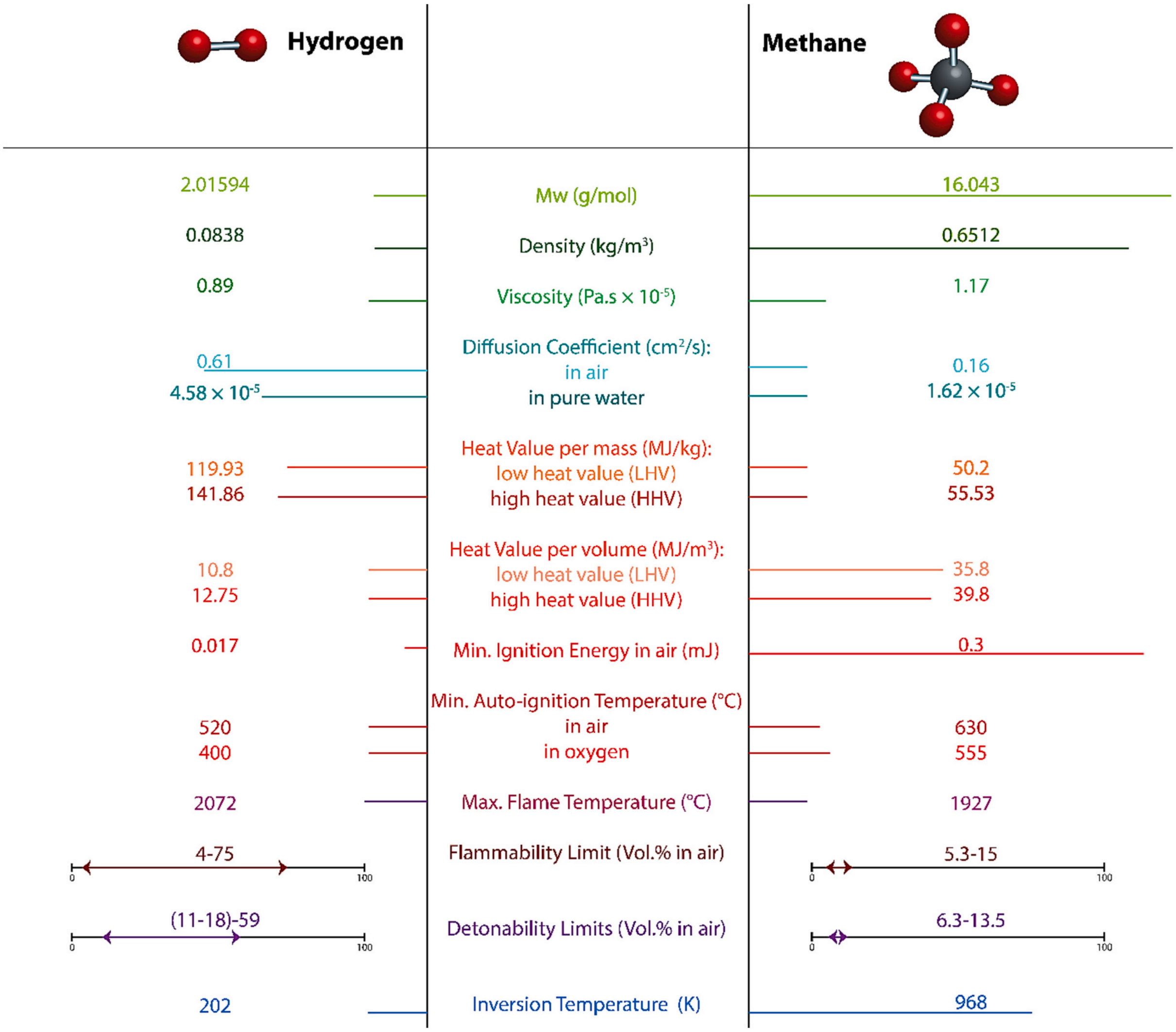

Fig. 6. Comparative analysis of the fundamental properties of hydrogen and methane. Data from [11,39,64–67].

exhibit smaller variations in terms of pressure and temperature compared to methane. These findings imply that thermal strains in a hydrogen gas storage system would likely be less pronounced than those observed in a natural gas storage system. Further, the study unveiled that most temperature changes in the surrounding rock mass occur within the first two meters. They utilized the results to assess the impact of thermal strains on the design of LRC.

3.1. Joule-Thomson effect

Hydrogen distinguishes itself from methane and most other gases, with the exception of helium and neon, in terms of the intriguing Joule-Thomson effect. This effect characterizes the temperature change that occurs during the expansion or flow of gas through a valve or porous plug under adiabatic conditions. Notably, hydrogen deviates from the norm as it experiences a unique response due to its distinctive molecular properties. While most gases cool down when expanding (corresponding to a positive Joule-Thomson coefficient), hydrogen takes a divergent path by heating up (displaying a negative Joule-Thomson coefficient) [68,69]. Hydrogen, along with helium and neon, are classified as quantum gases [69,70]. Quantum gases exhibit behaviors that classical physics cannot fully explain, requiring quantum mechanics to understand their unique thermal properties due to quantum effects, especially at low temperatures. For these gases the inversion temperature is higher than the critical temperature.

The inversion temperature is the specific temperature at which the sign of the Joule-Thomson coefficient changes from positive to negative or vice versa. For hydrogen, the inversion temperature at 1 atm is 202 K, which is higher than its critical temperature (33.2 K) [68,69].

This distinction can be attributed to the interplay of intermolecular forces as pressure and temperature fluctuate. Hydrogen molecules have very weak intermolecular forces due to their low molecular mass and small size. This means that the attractive forces between hydrogen molecules are relatively weak compared to other gases. For instance, gases with stronger intermolecular forces, such as methane, cool upon expansion as significant energy is absorbed to overcome these forces. In contrast, during hydrogen expansion, the weak intermolecular forces cannot effectively counteract the repulsive forces between the molecules. As hydrogen gas expands, the molecules move further apart, and the repulsive forces dominate, leading to an increase in kinetic energy and, consequently, temperature.

The practical implications of hydrogen's unique Joule-Thomson effect are significant, particularly in industrial applications requiring gas liquefaction and compression. The understanding of hydrogen's thermal response is crucial for optimizing process efficiency, informing the design of systems that can accommodate its heating upon expansion.

3.2. Hydrogen embrittlement

Hydrogen embrittlement is another significant concern in the storage of hydrogen in LRCs. Unlike natural gas, hydrogen can compromise the mechanical properties and structural integrity of the steel lining through hydrogen embrittlement. This phenomenon occurs when hydrogen atoms diffuse into the steel structure, leading to a reduction in its strength at grain boundaries and other vulnerable locations. It can cause the formation of microcracks and fissures, degradation, and a decrease in the lifespan of the lining. Hydrogen embrittlement is a widely studied subject in the existing literature, and there are a number of factors that can influence its severity such as metal composition and atomic structure, stress level, hydrogen concentration, pressure, and temperature [71–73].

In the context of lined rock caverns, the cyclic temperature and pressure variations resulting from gas injection and withdrawal processes can exacerbate the risk of embrittlement. Welded connections are particularly susceptible to embrittlement due to temperature changes, vulnerable microstructures, and residual stress. To mitigate the severity of hydrogen-induced damage, various measures can be implemented. These include minimizing hydrogen contact or mobility within the material. This can be achieved by reducing hydrogen pressure, utilizing corrosion-resistant alloys (low to intermediate carbon steels, austenitic structures), applying coatings as barriers against hydrogen diffusion, or employing novel surface treatment methods like helium implantation or ion irradiation for "hydrogen trapping" [35,71,74–76]. Although careful testing is required to select the appropriate steel type for hydrogen storage in LRC facilities, it is considered achievable [35].

4. Experience in lined cavern

While underground storage of hydrocarbons has been an established practice for decades, the use of lined rock caverns remains relatively limited. This is primarily due to the prevalence of experiences involving the storage of liquid hydrocarbons, where lining is not necessary, or in cases of storing liquids with higher vapor pressure, such as LPG or LNG, sealing is traditionally achieved via groundwater management techniques like water curtains. A wide range of experiences in liquid hydrocarbon storage exists globally, and the following examples provide some insights into this realm.

For instance, South Korea has been using unlined rock caverns by using water curtain for confinement as underground stockpiling facilities for the last 50 years [77]. Similarly, India has established excavated rock caverns at different locations, such as Visakhapatnam in the east and Mangaluru and Padur in the west, as strategic oil storage facilities to mitigate potential supply disruptions [78,79].

In 2014, Singapore launched the world's first undersea cavern for hydrocarbon storage, situated 130 m below Jurong Island. The project cost US$1.3 billion and comprised five caverns with dimensions of 20 m (width), 27 m (height), and 340 m (length), providing a total storage capacity of 1.47 million cubic meters. These unlined caverns utilize water curtains for secure storage [80–82].

In addition to several oil stockpiling bases in rock caverns, Japan also boasts two of the largest unlined rock cavern storage facilities for LPG. The Kurashiki facility consists of four caverns with a total volume of 820,000 m^3, capable of storing 400,000 tons of propane at 950 kPaG and 22 °C. On the other hand, the Namikata facility has three caverns with a total volume of 910,000 m^3, providing storage for 150,000 tons of combined butane-propane at 240 kPaG and 21 °C, as well as 300,000 tons of propane at 970 kPaG and 21 °C. These storage systems were completed in 2012, facilitating long-term LPG stockpiling operations [40,83].

Norway also has a rich history of underground hydrocarbon storage that dates to the 1970s, benefiting from its extensive experience in underground hydropower plants. An average of 300,000 m^3 of caverns has been annually excavated for storage purposes in Norway from 1975 to 2020. Among the notable facilities are Mongstad, boasting a capacity of 1.3 million m^3, and Sture, with a capacity of 1 million m^3. Detailed information on Norwegian hydrocarbon storage caverns can be found in the work by [84].

In contrast to liquid storage, gas storage requires a greater emphasis on gas tightness. Natural gas storage in coal mines, as seen in Belgium and the USA, serves as an important example [85,86], with detailed information provided in Table 1 (highlighted in gray). The operational pressure of these gas storage mines depends on the geological conditions and water pressure. Gas adsorption on coal is a significant mechanism in these settings, with ongoing investigations into its feasibility for H_2 [87–89].

Furthermore, LRC can also be utilized for underground compressed air energy storage (CAES) projects [54,90]. A successful pilot project for CAES in LCRs was performed in an abandoned coalmine in Hokkaido, Japan in 1990 [54,91]. Another pilot for confirming the validity of using LCR for natural gas storage in Japan was performed in Kamioka mine from 2004 to 2007 [92].

Moreover, South Korea executed a pilot project for liquefied nitrogen in 2004 [93,94]. The details of this project are in Table 1. A pilot of underground CAES has also been reported with the maximum pressure of 5Mpa in that facility [58,95,96].

China has also engaged in a pilot CAES project, evaluating the potential of CAES in LRCs in granite rock caverns at shallow depth within the Pingjiang pumped storage hydropower (PSH) tunnel [57].

In the late 1980s, Sweden began to explore the concept of gas storage in LRCs. This was due to the absence of geological conditions for conventional gas storage types and Sweden's long tradition of storing oil in unlined rock caverns. The initiative began with conceptual studies in 1995, followed by the construction of a pilot plant at Grängesberg from 1988 to 1989, which underwent testing from 1989 to 1993. The pilot plant served as a testing ground for various lining materials, the drainage system's functionality, the behavior of the rock and lining under cyclic loads, and the consequences of liner leakage under high pressure.

The success of the Grängesberg pilot plant and the following techno-economic studies led to the establishment of a demonstration plant at Skallen near Halmstad in south-western Sweden. Construction spanned from late 1998 to the summer of 2002. Extensive scientific testing was conducted at the Skallen plant, yielding promising results. The rock mass has demonstrated a response in line with expectations, and overall, the deformation level has been lower than anticipated. The Demo Plant has successfully met the stipulated criteria for storage capacity and deliverability. As a result, in 2004, the Skallen plant was converted into a commercial operation. LRCs exhibit potential operational profiles akin to salt caverns, with estimated annual turnover frequencies of 10–12, although the Skallen storage has operated at a lower intensity (1–2 annual turnovers) due to various factors [31,32].

To date, there is no previous experience of underground hydrogen storage in LRCs. However, a LRC is under development as part of the HYBRIT collaborative project that aims to produce fossil-free steel by using hydrogen in Luleå, Sweden. HYBRIT envisions the establishment of a substantial hydrogen gas storage facility with a capacity exceeding 65 GWh, featuring a full-scale design spanning 100,000 to 120,000 cubic meters. This lined rock cavern, positioned 30 m underground within red granite bedrock and reinforced with cement and steel linings, serves as a testing ground until 2024. In June 2022, the HYBRIT demonstration facility, boasting a volume of 100 m^3 and operating at pressures below 250 bar, was inaugurated in Luleå. Funded with SEK 331 million (USD 33 million), it aims to run until 2024. Future plans involve constructing a full-scale facility encompassing approximately 100,000 to 120,000 cubic meters (equivalent to 65 GWh of H_2 storage) [35].

5. Economy

The economic aspect of a project stands as a paramount factor, if not the most crucial since economic viability plays a decisive role in obtaining authorities' approval. Given the scarce experience with gas storage in LRCs and the absence of prior H_2 storage experience, the current estimates for investment costs harbor significant uncertainties. Additionally, the costs for underground gas storage also significantly impacted by local conditions, such as personnel costs (salary level) and pre-existing geological knowledge as well as global market conditions, such as the price of steel and fuel [7,18,34,100]. Furthermore, the cost of hydrogen storage is influenced by site-specific characteristics, such as the type of rock, which can impact excavation costs or the number of cycles [7].

Various economic analyses concerning hydrogen storage in LRCs can be found in the literature [7,18,20,100,101]. However, the results may vary to some extent due to the aforementioned factors. Nonetheless, all these studies indicate that hydrogen storage in LRCs is a costly undertaking. For instance, a study by [7] estimated the levelized cost of storage (LCOS) in a 580,000 m^3 hard rock cavern to be 2.77 $/kg (2007 $US), which is almost twice as expensive as other geological storage options. However, it is important to note that their estimation did not include the cost of steel lining, and the size and depth of their hard rock cavern were the same as their salt cavern (580,000 m^3 and 1158 m), which may not be suitable for a lined rock cavern. Additionally, their assumption of 30 % cushion gas is considered excessive for LRC applications.

In the context of green steel production, a notable study by [101] compared two H_2 storage options: chemically bound storage in CH_3OH and gaseous storage in LRCs. Their analysis revealed that neither storage option demonstrated overall profitability when considering historic electricity prices. However, the CH_3OH-based storage was found to have an economic advantage over the LRC storage [100,101].

The economic viability of underground storage typically improves as the storage capacity increases. For large-scale hydrogen storage, LRCs can offer cost advantages compared to certain alternatives, such as above-ground storage or underground pipeline storage. A study conducted by [20] argued that for storage capacities exceeding 20 tons of H_2, LRCs are more economical than underground pipes, although they remain more expensive compared to salt caverns. Similarly, for storing 20 million barrels of crude oil, the construction cost of underground storage facilities is 15 % lower compared to aboveground storage. Similarly, for LPG storage, the breakeven point is reached at 60,000 tons [77]. However, it is of utmost importance to emphasize that achieving larger storage volumes in LRCs beyond a certain point requires the excavation of multiple caverns next to each other, which inevitably leads to diminishing economy of scale [20,100]. In contrast, salt caverns showcase better scalability due to their higher maximum H_2 storage capacity. For example, when analyzing the CAPEX per unit of working gas, LRCs showed only about 6 % variation between a single cavern facility (e.g., Skallen with 640 tons of H_2) and a four-cavern facility (4340 tons of H_2) [18,34]. Similarly, the total investment cost for an eight-cavern facility was estimated to be 1.89 times higher than the four-cavern facility, resulting in just around 6 % more cost per unit of stored gas [34].

6. Conclusion, technical challenges, and further outlook

LRCs have traditionally been acknowledged for their feasibility as storage solutions, primarily for natural gas. Transitioning this approach for hydrogen storage introduces both familiar and unprecedented challenges, chiefly due to hydrogen's distinct properties. In the following paragraphs, we will summarize some key challenges and research gaps specifically related to LRCs for hydrogen storage.

One of the primary concerns is hydrogen embrittlement of the steel lining, which could compromise the integrity of storage structures. To address this, focused research and development initiatives are imperative. The focus should not only encompass the exploration of materials resilience against hydrogen interactions but also the underlying mechanisms of embrittlement at the microstructural level. Innovative advancements, like the development of novel coatings or surface treatments, could prove invaluable.

Beyond hydrogen embrittlement, it's critical to investigate the long-term effects of hydrogen exposure on all materials within the cavern. This includes studying how sealing materials and electronic monitoring equipment might degrade over time. The investigation should prioritize material compatibility, aiming to enhance resistance to hydrogen-induced degradation. This effort will involve evaluating alternative materials and coatings that can withstand such effects, as well as verifying the durability of sensors and monitoring equipment in the hydrogen storage environment.

A rigorous testing regime is indispensable. Evaluating materials, especially the behavior of sliding layers sandwiched between steel and concrete, under diverse conditions will provide insights into degradation processes and influence optimal material selection. Moreover, the industry's experience with rock caverns for high-pressure gas storage is still in its infancy, necessitating extensive long-term stability assessments. Collaborative efforts, integrating laboratory tests and field studies, should be intensified to ensure the reliability of LRCs for extended durations.

Understanding the need for effective thermal management in LRCs is crucial, as temperature variations during hydrogen injection and withdrawal may significantly affect the cavern. These changes highlight the importance of designing thermal regulation systems to ensure the structural integrity and efficiency of operations. Thermal management might be a challenge, particularly due to hydrogen's unique thermal properties and the effects of pressure changes and the Joule-Thomson effect. Developing systems to control these thermal dynamics is important for maintaining the stability and functionality of LRCs.

Challenges related to ensuring operational flexibility, such as rapid cycling between hydrogen storage and release, and maintaining reliability over long periods, could be further explored. Optimizing the energy efficiency of hydrogen injection and withdrawal processes presents a technical challenge, necessitating the development of methods to minimize energy consumption while maintaining high operational performance.

Environmental considerations are paramount. While hydrogen poses a lesser environmental treat in leakage scenarios compared to other gases, potential chemical or biological interactions within the host rock might have long-term ecological implications. For instance, biological clogging in the drainage system, an often-overlooked aspect, warrants comprehensive research to ensure environmental compatibility.

Economic feasibility and scalability of LRCs remains at the forefront of implementation challenges, particularly for large-scale applications. Although LRCs might initially present a costlier alternative for hydrogen storage compared to other geological options, further research is essential to deepen our understanding of these aspects. It should focus on comprehensive cost analyses and alternative scalability evaluations, aiming to elucidate the potential economic implications and feasibility of expanding LRCs for widespread use. A comprehensive analysis factoring in local geological conditions, global market dynamics, and potential local storage capacities could reveal a more refined economic landscape.

As the regulatory framework for hydrogen storage continues to evolve, understanding the impact of both existing and forthcoming safety standards on LRC design and operation becomes crucial. The changing nature of these regulatory and safety requirements underscores the need for continuous research to maintain compliance and integrate new safety measures. This effort must also consider the seismic resilience of LRCs, particularly the enhancement of their design and operational protocols to mitigate risks in seismically active areas.

In addition to the technical and economic challenges, gaining public trust and acceptance is crucial for the successful implementation of LRCs for hydrogen storage. Transparent and engaging communication strategies that highlight the safety and environmental benefits of LRCs are necessary to address public concerns and foster a supportive environment for these innovative storage solutions.

In the march towards a sustainable energy future, LRCs for hydrogen storage present both a promise and a puzzle. With dedicated research, informed by past experiences and steered by innovative approaches, we could unlock an efficient and sustainable storage solution for the energy vector of the future.

CRediT authorship contribution statement

Mohammad Masoudi: Writing – original draft, Visualization, Methodology, Investigation, Funding acquisition, Conceptualization. **Aliakbar Hassanpouryouzband:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization. **Helge Hellevang:** Writing – review & editing, Supervision, Resources, Funding acquisition. **R. Stuart Haszeldine:** Supervision, Resources.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

Acknowledgments

M.M. and H.H. acknowledge the funding received for this study from the HYSTORM projects "clean offshore energy by hydrogen storage in petroleum reservoirs" (funded by Research Council of Norway under grant number 315804). The authors acknowledge UiO:Energy and Environment for the seed funding for research and research collaboration within sustainable energy, climate, and the environment. Some of the small icons of Figs. 1 and 3 were taken from Freepik.com, created by "macrovector".

Supporting information

The explanation of the terms in Fig. 6 is as follows:

Heat value: the amount of energy released when hydrogen reacts with oxygen to form water. The liberated energy can be measured based on volume or mass, resulting in different measures of energy density. Hydrogen holds the highest mass energy density among conventional fuels, meaning that a smaller amount of hydrogen by weight can deliver the same amount of energy compared to other fuels. Conversely, hydrogen has the lowest volumetric energy density, meaning that a larger volume (at the same pressure and temperature) is required to store the same amount of energy as other conventional fuels. The energy density of hydrogen can be differentiated between low heat value (LHV) and high heat value (HHV). The difference between LHV and HHV is due to the energy released when water vapor condenses. If the water vapor is in the vapor phase, the energy release is referred to as LHV or net calorific value. If the water vapor is in the form of liquid water, the energy release is referred to as HHV or gross calorific value [65].

Flammability range: The concentration range of a gas in air where it can sustain a self-propagating flame when ignited. Under ambient conditions, hydrogen has a broad flammability range (4–75 %).

Minimum auto-ignition Temperature: The lowest temperature at which a substance can spontaneously ignite without an external ignition source.

Minimum ignition energy (MIE): the lowest energy required for ignition of a material.

Maximum Flame Temperature: The temperature of the flame produced during combustion at near stoichiometric mixtures.

Detonability limit: Refers to the concentration range within which a fuel can detonate, an abrupt and violent form of combustion.

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