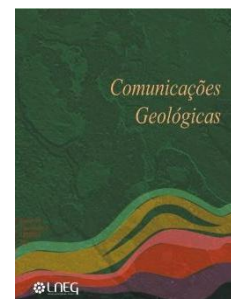


Site screening requirements for hydrogen geological storage in saline aquifers

Requisitos para a seleção de locais para o armazenamento geológico de hidrogénio em aquíferos salinos

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Abstract: Underground hydrogen storage (UHS) in deep saline aquifers is a promising solution for large-scale, long-duration energy storage, vital for addressing renewable intermittency and enabling deep decarbonization. This study presents a benchmarking of requirements and a comprehensive framework for site screening of saline aquifers for hydrogen storage. It integrates technical parameters – such as reservoir quality, seal integrity, and geomechanical stability – with non-technical aspects, including economic viability, regulatory readiness, environmental risk, and social acceptance. Particular focus is given to hydrogen-specific challenges affecting storage integrity, especially geochemical and geomechanical factors. Drawing from experience with natural gas and CO₂ storage, the study proposes a multidisciplinary screening workflow to support early-stage project assessment. The findings provide a foundation for future pilot projects, policy development, and regulatory frameworks tailored to UHS in porous media, contributing to the strategic expansion of hydrogen infrastructure and energy system resilience.

Keywords: Underground hydrogen storage, technical and non-technical criteria, saline aquifers, site screening, energy transition.

Resumo: O armazenamento subterrâneo de hidrogénio (ASH) em aquíferos salinos profundos representa uma solução promissora para o armazenamento de energia em grande escala e de longa duração, essencial para lidar com a intermitência das renováveis e permitir uma descarbonização profunda. Este estudo apresenta uma análise comparativa dos requisitos e um quadro abrangente para a seleção de locais adequados ao armazenamento de hidrogénio em aquíferos salinos. Integra parâmetros técnicos – como a qualidade do reservatório, a integridade da camada selante e a estabilidade geomecânica – com aspetos não técnicos, incluindo viabilidade económica, preparação regulatória, riscos ambientais e aceitação social. Dá-se especial atenção aos desafios específicos do hidrogénio que afetam a integridade do armazenamento, nomeadamente fatores geomecânicos e geoquímicos. Com base na experiência de armazenamento de gás natural e de CO₂, é proposto um fluxo de trabalho multidisciplinar para apoiar a avaliação em fases iniciais. As conclusões constituem uma base para projetos-piloto, desenvolvimento de políticas e enquadramentos regulatórios adaptados ao ASH em meios porosos, contribuindo para a expansão estratégica da infraestrutura do hidrogénio e para a resiliência do sistema energético.

Palavras-chave: Armazenamento geológico de hidrogénio, critérios técnicos e não-técnicos, seleção de locais, aquíferos salinos, transição energética.

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1. Introduction

The contribution of fossil fuels to the global energy mix has gradually decreased over the last 10 years, from 82% in 2013 to 80% in 2023 (IEA, 2024). Although renewable energy sources have contributed to this reduction, their inherent intermittency – particularly in wind and solar generation – presents a major challenge, as periods of production and consumption rarely align (Miocic *et al.*, 2023). One way to overcome this mismatch is through the conversion of surplus renewable energy into hydrogen via electrolysis, which can then be stored in geological formations and recovered later for use in fuel cells, turbines, or boilers (Hematpur *et al.*, 2023).

Underground hydrogen storage (UHS) has been practiced for decades, but knowledge of the specific requirements for pure hydrogen gas (H₂) storage in porous geological media remains limited compared to more mature gases like natural gas. Although commercial-scale hydrogen storage currently relies primarily on salt caverns – such as those in Teesside, UK, in operation since 1972 – there is significant historical experience with storing hydrogen-rich gas mixtures (*e.g.*, “town gas”), including the aquifers in Engelbostel, Hähnlein, Eschenfelden, and Ketzin (Germany), the depleted gas field in Kirchheiligen (Germany), the aquifer in Lobodice (Czechia), and the aquifer in Beynes (France), typically containing 30–50% hydrogen (*e.g.*, Zivar *et al.*, 2021; Tarkowski *et al.*, 2021; Bouteldja *et al.*, 2021; Sambo *et al.*, 2022; Okoroafor *et al.*, 2022; Raza *et al.*, 2022; Raad *et al.*, 2022; Epelle *et al.*, 2022; Miocic *et al.*, 2023).

Despite this precedent, the scientific literature still lacks a comprehensive framework for evaluating pure hydrogen storage specifically in deep saline aquifers, although some efforts have been recently conducted for the long-term storage of hydrogen based on realistic seasonal and hourly cyclic profiles with

promising results for UHS (Pereira *et al.*, 2025). This work aims to address this gap by compiling and assessing the key criteria – technical and non-technical – required for site selection, building upon methodologies developed in enhanced oil and gas recovery, natural gas storage, and carbon dioxide (CO₂) sequestration projects to ensure the efficiency and safety of cyclical hydrogen injection and withdrawal operations.

An understanding of the intrinsic physical and chemical properties of hydrogen is essential in determining the suitability of geological formations for storage. According to Ciotta and Tassinari (2024), hydrogen molecules are approximately eight times smaller than methane (CH₄) and twenty-two times smaller than CO₂, making H₂ significantly more prone to diffusion and leakage. Likewise, the lower density and high mobility ratio of H₂, compared to CH₄ and CO₂, require greater injection pressures for storage, and that the integrity of caprocks must be particularly robust, meaning that a geological environment capable of containing CH₄ will be able to contain CO₂, but the same might not be true for H₂ (Hematpur *et al.*, 2023). Hydrogen can also react with reservoir rocks and seal materials, potentially leading to losses via mineral dissolution, precipitation, and microbial processes. A detailed characterization of the sealing performance and reservoir geochemistry for the selection of adequate sites for UHS in geological formations – particularly in porous geological formations such as deep saline aquifers, is critical and, therefore, these key factors will also be addressed in more detail in this work.

2. Underground hydrogen storage

The large-scale integration of renewable energy sources such as wind and solar into the global energy mix has intensified the need for efficient and safe long-term energy storage systems. Among the various options available, underground hydrogen storage

(UHS) in geological formations presents one of the most promising solutions to overcome the intermittency of renewables, offering large capacities, spatial flexibility, and lower environmental exposure compared to surface storage alternatives (Mehr *et al.*, 2024; Goodman *et al.*, 2022).

2.1. Hydrogen storage options in geological media

Hydrogen can be stored in several types of geological formations, including salt caverns, abandoned mines and in porous geological media, *i.e.*, depleted hydrocarbon fields and deep saline aquifers (Mehr *et al.*, 2024; Fuentes and Santos, 2023; Nicol *et al.*, 2022). Among these options (Fig. 1), subsurface geological formations offer larger capacity lower risk, and better safety conditions compared to surface storage systems. Their deep locations isolate the stored gas from external hazards such as oxygen, ignition sources, and environmental disturbances (Goodman *et al.*, 2022), resulting in a lower impact in terms of surface occupation, requiring less land area (better territorial management), and construction costs are significantly lower when compared to storage in surface tanks.

Salt caverns are leached into rock salt formations at depths of 1000–2000 m. Their cylindrical geometry (typically 300–500 m high and 50–100 m wide) can support pressures of 100–250 bar, providing energy capacities of 200–300 GWh (Michalski *et al.*, 2017, as cited by Mehr *et al.*, 2024). However, scaling this technology for national or continental hydrogen storage would require hundreds of caverns.

Abandoned or excavated rock caverns and lined mines also offer potential for hydrogen storage. Typically, these structures are excavated in igneous and metamorphic rocks (*i.e.*, in granites or basalts), consisting of one or more galleries developed in vertical shafts or inclined drifts with depths of up to 300 m. These systems

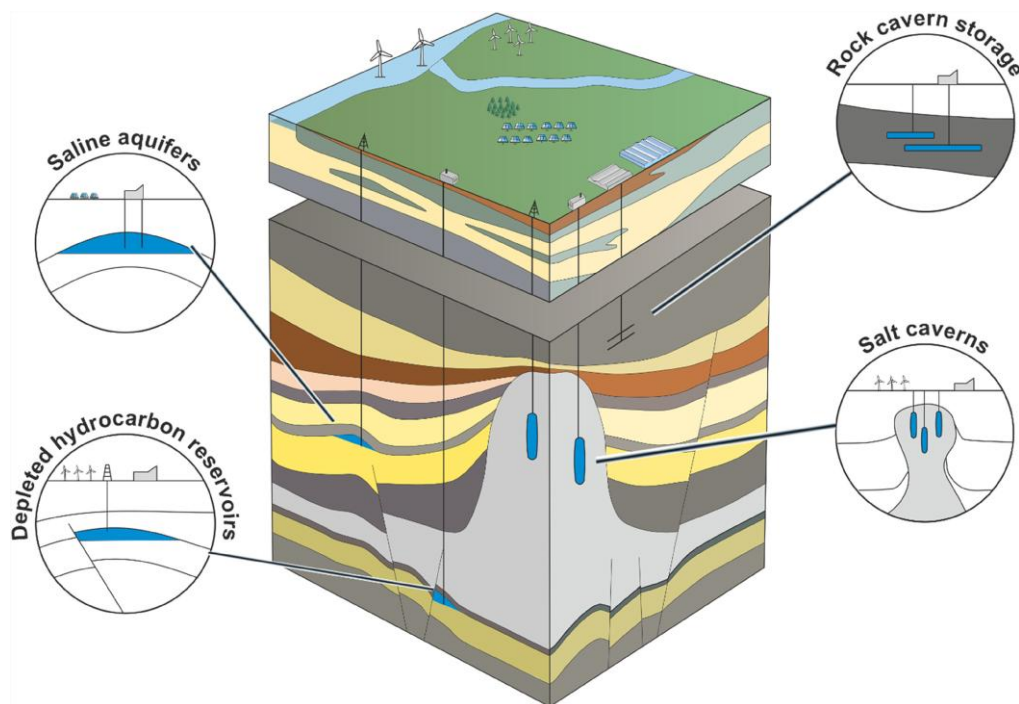


Figure 1. Types of underground hydrogen storage (Miocic *et al.*, 2023).

Figura 1. Tipos de armazenamento subterrâneo de hidrogénio (Miocic *et al.*, 2023).

often employ concrete or steel linings to maintain structural integrity, gas containment and chemical resistance under high pressure (> 200 bar) (Diamantakis *et al.*, 2024; Nicol *et al.*, 2022).

Depleted oil and gas fields are among the most attractive options due to their known geology and existing infrastructure. They consist of porous and permeable sedimentary rocks located beneath an existing impermeable caprock (Hematpur *et al.*, 2023). Among the introduced storage options, depleted hydrocarbon fields present larger storage capacity (BNEF, 2020; Walsh *et al.*, 2023) and are widely distributed compared to salt caverns (Zivar *et al.*, 2021). These reservoirs typically have proven caprock seals and well-documented flow behaviour. Pressures and depths can range from 150 – 300 bar and 300 – 2700 m, respectively (Hematpur *et al.*, 2023). Because of their extensive global distribution and high capacity, they are frequently prioritized for hydrogen storage projects (Zivar *et al.*, 2021; Walsh *et al.*, 2023).

2.2. Suitability of deep saline aquifers

Deep saline aquifers consist of porous sedimentary rocks saturated with brine and overlain by impermeable seals (Sambo *et al.*, 2022). These are geological layers located from hundreds to thousands of meters depth and rely on the trapping mechanisms to prevent hydrogen from escaping laterally and vertically from the storage formation (Mehr *et al.*, 2024). They are often found at depths ranging from 400 to 2300 m and operate at pressures between 30 and 300 bar (Hematpur *et al.*, 2023). Saline aquifers present a significant opportunity for cost-effective long-term hydrogen storage due to the potential larger storage capacity (billions of cubic meters) – sometimes larger than depleted oil and gas fields – and more widely distributed geographically, often in proximity to renewable energy hubs (Raad *et al.*, 2022). The need to assess the viability these geological formations for hydrogen storage purposes is essential to successfully implement large-scale storage operations as not all promising options are suitable for commercial-scale purposes (Raad *et al.*, 2022).

For successful storage, aquifers must have favourable reservoir quality (high porosity and permeability) and be overlain by adequate, low permeability caprocks that acts as a seal to prevent the vertical migration of hydrogen (Sambo *et al.*, 2022), as illustrated in figure 2. Moreover, the presence of effective structural or stratigraphic traps is essential to ensure lateral containment (Mehr *et al.*, 2024). Hydrogen storage in deep saline aquifers develops by injecting a “cushion gas” into an aquifer (Hematpur *et al.*, 2023). When H_2 is injected into an aquifer that is filled with water (brine), the difference in density between the gas and the liquid results in the brine displacement downwards or sideways (Zivar *et al.*, 2021; Mehr *et al.*, 2024), forming a buoyant gas cap. A fraction of the injected hydrogen, known as the “cushion gas,” remains in place to maintain reservoir pressure and stabilize cycling operations. The remaining “working gas” is subject to cyclic injection and withdrawal (Zivar *et al.*, 2021; Mehr *et al.*, 2024). Cushion gases may include H_2 itself, nitrogen (N_2), or CO_2 , although CO_2 can introduce additional separation challenges due to contamination, requiring a proper separation process at the surface facilities.

2.3. Challenges of hydrogen behaviour in subsurface conditions

The behaviour of hydrogen in subsurface environments differs significantly from that of methane or CO_2 . Its small molecular size, high diffusivity, and low viscosity contribute to increased mobility and a higher risk of leakage through microfractures or caprock diffusion pathways (Ciotta and Tassinari, 2024; Heinemann *et al.*, 2021). Additionally, hydrogen can react geochemically with minerals in both the reservoir and the seal, altering porosity and generating by-products such as H_2S or CH_4 (Raad *et al.*, 2022; Braid *et al.*, 2024).

Microbial consumption of hydrogen by sulfate-reducing bacteria or methanogens may lead to gas loss and the accumulation of undesirable gases. These processes are more pronounced in formations with low salinity, moderate temperatures (< 80 °C), and

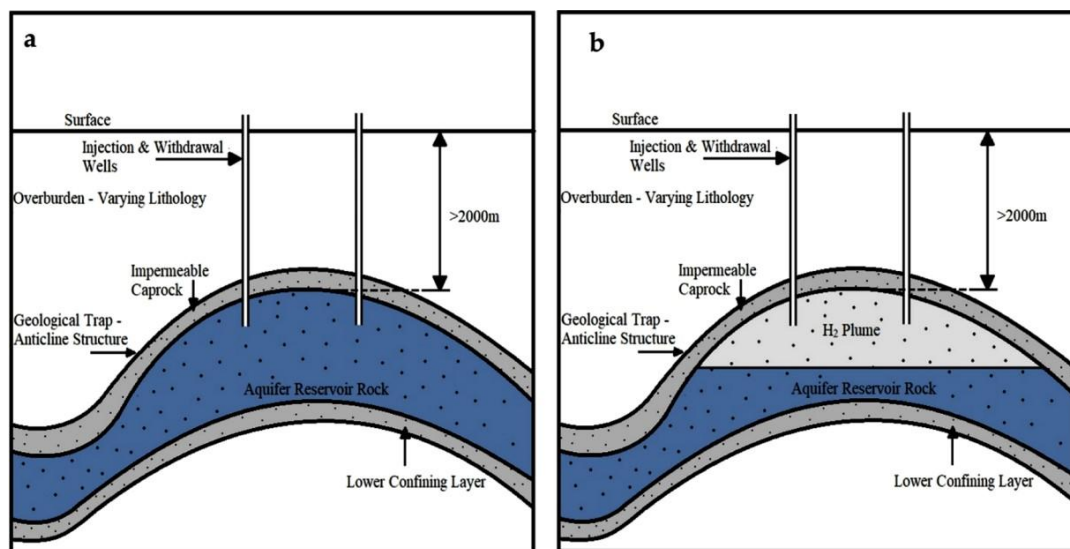


Figure 2. Schematic representation of underground hydrogen storage in deep saline aquifers: (a) aquifer before hydrogen injection, (b) aquifer after hydrogen injection (Hematpur *et al.*, 2023).

Figura 2. Representação esquemática do armazenamento subterrâneo de hidrogénio em aquíferos salinos: (a) aquífero antes da injeção de hidrogénio, (b) aquífero após a injeção de hidrogénio (Hematpur *et al.*, 2023).

active microbial communities (Muhammed *et al.*, 2022; Raad *et al.*, 2022).

Hydrogen injection also induces cyclic geomechanical stresses, potentially affecting reservoir compaction, fracture propagation, and caprock integrity (Kumar *et al.*, 2023). Therefore, comprehensive modelling of rock mechanical behaviour, pressure build-up, and fault stability is necessary to prevent containment failure.

In light of these challenges, screening of adequate storage sites for H₂ requires the evaluation of several criteria, such as technical, economic, health and safety and environmental (HSE) and social (Nemati *et al.*, 2020; Harati *et al.*, 2024), and must incorporate a multidisciplinary approach combining geology, geomechanics, microbiology and geochemistry.

This work presents a benchmarking of these requirements, compiled and adopted in the H2GeoStore project, which were grouped in both technical and non-technical criteria. This should be taken into consideration when selecting areas for the safe and efficient storage of H₂ in deep saline aquifers. In addition, a general discussion is presented at the end of this work, by proposing a conceptual framework for the preliminary screening of UHS sites in deep saline aquifers and presenting several final remarks and insights in this thematic.

3. Technical requirements for UHS in deep saline aquifers

Geological aspects are of paramount importance, corresponding to the first premises to be considered in evaluating and selecting sites for hydrogen storage in geological formations. The candidate site must guarantee the existence of formations with adequate reservoir properties, which according to Alms *et al.* 2023, allow for a high storage volume, as well as high gas injection and recovery rates. It must guarantee the existence of a caprock above the reservoir which must be reasonably thick and impermeable, crucial to prevent any risk of hydrogen escaping to the surface or adjacent layers (Fuentes and Santos, 2023). Several positive and cautionary indicators for UHS site selection in deep saline aquifers are presented in table 1. In addition, several important technical criteria that can disqualify sites selection for UHS are also presented in table 2. These aspects are presented and discussed in more detail in the next sections.

3.1. Reservoir Properties

A deep saline aquifer suitable for UHS must exhibit favourable reservoir properties that ensure adequate pore volume for gas injection and storage, high injectivity and recovery rates, as well as geochemical stability. These reservoir characteristics are intrinsically related to the petrophysical, mineralogical and structural composition of the rock matrix, and directly influence the feasibility and safety of UHS operations (Alms *et al.*, 2023; Uliasz-Misiak and Misiak, 2024).

3.1.1. Porosity and permeability

Porosity and permeability are fundamental petrophysical parameters to assess reservoir adequacy for hydrogen storage. According to Uliasz-Misiak and Misiak (2024), porosity values above 15% and permeability above 50 millidarcies (mD) are considered minimum thresholds for viable UHS projects, while Alms *et al.* (2023) suggest optimal values exceeding 20% porosity and 500 mD permeability. These parameters define the pore volume available for gas injection and the flow capacity of the rock matrix, directly impacting injection rates, pressure build-up, and hydrogen deliverability.

From a depositional standpoint, high-energy environments such as fluvial channels or shallow marine bars tend to produce well-sorted, porous, and permeable sandstones with better connectivity. In contrast, fine-grained or clay-rich facies, as well as those affected by diagenetic compaction, often exhibit lower permeability and capillary-driven flow resistance, limiting hydrogen mobility and storage performance (Tarkowski and Uliasz-Misiak, 2022).

3.1.2. Mineralogical composition and geochemical compatibility

Several authors have drawn attention to the aspect of chemical and mineralogical composition of rocks (Muhammed *et al.*, 2022; Braid *et al.*, 2024; Bai *et al.*, 2014). The mineralogical composition of the reservoir rock plays a crucial role determining its geochemical compatibility with hydrogen gas, impacting the success of storage projects in porous geological media, particularly in deep saline aquifers. Sandstones and, to lesser extent,

Table 1. Positive and negative indicators for underground hydrogen storage in deep saline aquifers based on literature (adapted: Alms *et al.*, 2023).

Tabela 1. Indicadores negativos e positivos para fins de armazenamento de hidrogénio em aquíferos salinos profundos baseados na literatura (adaptado: Alms *et al.*, 2023).

Requirement	General indicator	H ₂ positive indicator	H ₂ cautionary indicator
Depth (m)	400 - 3500	1100	< 800 > 3700
Area (km ²)	0.3 - 60		
Thickness (m)	3 - 100		
Caprock thickness (m)	> 50		
Lithology	Sandstone, Limestone	Sandstone	
Caprock lithology	Salt layers, Anhydrites, Clay and rocks with medium permeability (Sandstones, Limestones and Dolomites)	Salt layers, Anhydrites and Clay	Formations rich in sulphates, carbonate and sulphide minerals
Porosity (%)	15 - 20	> 20	
Permeability (mD)	50 - 500	> 500	
Salinity (g/L)		> 100	< 100
Temperature (°C)		> 40	< 40
pH		< 6	> 8

Table 2. Technical and no-technical disqualifying thresholds for underground hydrogen storage (adapted: Okoroafor *et al.*, 2022).

Tabela 2. Limiares de desqualificação técnica e não técnica para o armazenamento subterrâneo de hidrogênio (adaptado: Okoroafor *et al.*, 2022).

Category	Criteria	Disqualifying Threshold
Storage and Withdrawal Optimization	Reservoir Pressure (bar/m)	Wellhead Pressure Constraint > Reservoir Pressure-(0.01) x Reservoir Top Depth
	Maximum Depth of Formation Top (m)	> 3000
	Permeability (mD)	< 50
	Porosity (%)	< 10
	Net-Reservoir Thickness (m)	< 10
Risk and Hydrogen Loss Minimization	Top Seal Thickness (m)	< 20
	Secondary Confining Units	No Secondary Confining Units
	Active/ Inactive Faulting	4km wide “buffer zone” around all Quaternary faults
	Earthquake Record	10 km diameter for M > 5 (from 1769-Present), 5 km diameter for M < 5 (from 2015-Present)
	Resources in the Reservoir	Oil and Gas Condensate
Environmental and Economic Considerations	City Nearby	Within City Boundaries
	Restricted Lands	Within Restricted Lands
	Sensitive Habitats	Within Sensitive Habitats
	Population Density (persons/ km ²)	Above 75
	Proximity to Source or Distribution Point (km)	>30 within Source of Hydrogen
	Access to existing Pipelines or Transport Facilities	No Access to existing Pipelines or Transport Facilities
	Land Ownership	Inability to secure Land Ownership for the Project

limestones, are preferred reservoir rocks for UHS due to their high porosity and permeability and their relatively low reactivity under subsurface conditions (Bai *et al.*, 2014; Alms *et al.*, 2023), thus allowing gas mobility and accumulation (Uliasz-Misiak and Misiak, 2024). Quartz-dominated sandstones offer favourable geochemical inertness, minimizing risks of hydrogen-induced mineral alteration.

Due to the characteristics of H₂, the interaction with geological media can result in potential gas losses through dissolution and precipitation mechanisms (Fig. 3), due to the weakening and loss of integrity of the caprocks (Alms *et al.*, 2023). Another aspect to consider is the issue of toxic gases, such as H₂S, SO₂, CO₂, which

can be generated and released, in case of leakage, to the surface because of these reactions. In general, geological formations rich in sulphates, carbonates and sulphide minerals are not recommended for UHS (Bai *et al.*, 2014). In addition, clays, especially smectite, also pose risks due to swelling and catalytic effects on hydrogen conversion (Fuentes and Santos, 2023), which may compromise the storage integrity (Braid *et al.*, 2024).

3.1.3. Reservoir facies distribution and heterogeneity

Beyond porosity and permeability, the spatial distribution of reservoir facies and heterogeneity at multiple scales is a key factor

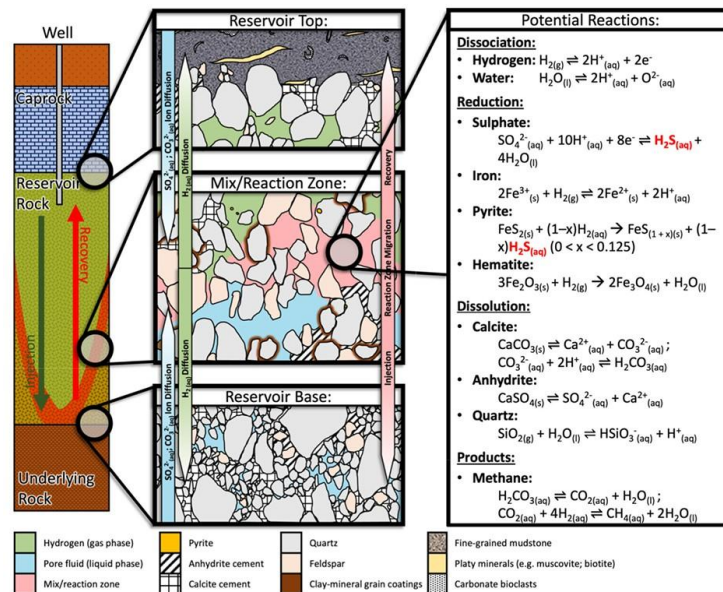


Figure 3. Main geochemical reactions that can dictate the conversion, contamination and loss of hydrogen stored in saline aquifers (Braid *et al.*, 2024).

Figura 3. Principais reações geoquímicas que podem ditar a conversão, contaminação e perda do hidrogênio armazenado em aquíferos salinos (Braid *et al.*, 2024).

in assessing the suitability of saline aquifers for underground hydrogen storage (UHS). Variations in lithology, grain size, cementation, and diagenesis influence the continuity of reservoir properties, often leading to compartmentalization and preferential flow paths that affect hydrogen migration and recovery (Diamantakis *et al.*, 2024; Raad *et al.*, 2022).

Facies heterogeneity can result in flow barriers, baffles, or isolated zones that cause uneven hydrogen plume movement and localized pressure anomalies during injection and withdrawal cycles (Heinemann *et al.*, 2021; Tarkowski and Uliasz-Misiak, 2022). Such conditions may reduce sweep efficiency and leave behind bypassed gas pockets. To accurately represent these complexities, geostatistical modelling and high-resolution sedimentological analysis are necessary (Alms *et al.*, 2023).

Suitable geological formations for UHS are characterized by laterally continuous, homogeneous sandstone units with minimal internal barriers, as these provide the most favourable conditions for hydrogen injection, containment, and recovery (Raad *et al.*, 2022).

3.2. Reservoir structure and depth

Structural configuration and depth are key geological aspects that govern the confinement and accessibility of hydrogen in subsurface formations. The geometry of the reservoir, the presence of faults, and the overburden pressure regime directly influence gas containment, risk of leakage, and economic viability of UHS.

3.2.1. Structural trapping and tectonic setting

Structural traps, such as anticlines, fault-bounded closures, or tilted fault blocks, are preferred for hydrogen storage due to their ability to create natural containment for the injected gas (Fuentes and Santos, 2023). These structures should present four-way closure and a continuous, intact caprock with sufficient areal extent to accommodate the hydrogen plume.

Tectonic stability is critical: regions affected by active faulting, folding, or neotectonics deformation may present a higher risk of leakage due to fault reactivation or caprock breach. According to Raad *et al.* (2022), aquifers located in tectonically stable sedimentary basins offer the best conditions for long-term storage.

Detailed structural mapping, fault seal analysis, and geomechanical modelling are necessary to assess the integrity of trapping configurations and the capacity of faults to retain gas under varying pressure regimes (Diamantakis *et al.*, 2024).

3.2.2. Depth and thickness considerations

Another important factor to consider when selecting areas for UHS is the reservoir depth, referring to the minimum depth required for storage. This is key for the safety and cost-effectiveness of implementing hydrogen storage projects. According to Alms *et al.* (2023), depths of more than 1200 m are not common in underground gas storage facilities, and therefore 1100 m is the ideal depth. However, there is a range of depth values reported in the literature (Tab. 1), such as depths between 400 - 2300 m (Hematpur *et al.*, 2023), and a minimum depth of 1000 m (Diamantakis *et al.*, 2024) and between 3000 - 3500 m as the maximum limit (Uliasz-Misiak and Misiak 2024). According to Alms *et al.*, 2023, the issue of limiting storage depth is purely economic; however, Uliasz-Misiak and Misiak (2024) consider that this reason is due to the potential deterioration of the petrophysical properties of the reservoir with depth.

Reservoir thickness is similarly an important aspect that directly affects the volume of hydrogen that can be stored and the distribution of pressure changes. The effective thickness of a reservoir or layers determines the potential H₂ storage volume (Sadkhan and Al-Mudhafar, 2024). Therefore, in deep saline aquifers, values ranging from 3 to 100 m are reported as reference values for reservoir thickness (Jahanbakhsh *et al.*, 2024). In addition, the lower the reservoir thickness, the higher is the potential of faster reservoir pressure build-up issues during the storage operations.

3.3. Diffusion, seal integrity and caprock performance

The storage of hydrogen in deep saline aquifers faces specific challenges related to its physical and chemical characteristics. Due to its extremely small molecular size, low density and high mobility, hydrogen is more prone to leakage compared to other gases such as CO₂ or CH₄. These properties raise serious concerns about caprock performance and long-term seal integrity under cyclical injection and withdrawal operations. Thus, understanding the interactions between hydrogen and the surrounding geological formations – particularly seal formations – is critical to ensure successful and safe underground hydrogen storage (UHS) operations.

3.3.1. Molecular diffusion and transport risks

Hydrogen molecules have a kinetic diameter of approximately 0.29 nm – significantly smaller than those of CH₄ or CO₂ – making them susceptible to diffusion through nanopores in both reservoir rocks and seals (Ciotta and Tassinari, 2024; Heinemann *et al.*, 2021). In tight formations, this molecular diffusion can become a dominant transport mechanism, particularly during static phases or low-pressure operation. Experimental and modelling studies have shown that hydrogen diffusivity in fine-grained sediments (*e.g.*, claystones, mudstones) may be one or two orders of magnitude higher than that of CO₂ (Fuentes and Santos, 2023; Alms *et al.*, 2023).

This process can lead to the gradual migration of hydrogen through low-permeability zones, potentially compromising the seal and reducing storage efficiency. Furthermore, in heterogeneous formations with microfractures or capillary networks, Knudsen diffusion and advective transport may also enhance hydrogen escape, particularly in under pressured formations or near faults (Raad *et al.*, 2022). Therefore, the assessment of diffusive fluxes must be integrated into reservoir simulation models, even in formations traditionally considered impermeable.

3.3.2. Caprock mineralogy, permeability and thickness

The selection of an appropriate caprock is fundamental to ensure the containment of stored hydrogen over extended periods. Effective seals must exhibit extremely low permeability (typically < 10⁻¹⁸ m²) and a homogeneous mineralogical composition dominated by non-reactive, ductile minerals (Diamantakis *et al.*, 2024). Evaporites such as halite and anhydrite are among the most suitable caprocks due to their self-sealing properties, very low porosity, and chemical inertness in the presence of hydrogen (Bai *et al.*, 2014; Alms *et al.*, 2023). Clay-rich shales can also be considered as suitable caprocks due to very low permeability and porosity; however, they may exhibit swelling behaviour or become chemically unstable when exposed to H₂-rich environments (Diamantakis *et al.*, 2024).

Moreover, thin or fractured caprocks may not be sufficient to withstand the buoyant pressure of hydrogen plumes. The existence of a thick caprock is important to ensure effective trapping and to prevent hydrogen from escaping from the reservoir to the geological layers above (or until the surface), as well as laterally. According to Jahanbakhsh *et al.* (2024), a minimum caprock thickness of 50 m is required to maintain hydraulic and mechanical sealing, although this threshold may vary based on lithology and in situ stress conditions.

The presence of reactive minerals (*e.g.*, pyrite, carbonates, iron oxides) within the seal may also result in hydrogen consumption or mineral alteration, reducing sealing efficiency. Thus, petrophysical and mineralogical characterization of the caprock – including microstructural analysis, geochemical reactivity and permeability mapping – is essential during site screening.

3.3.3. Cyclic geomechanical effects and leakage risks

Repeated cycles of hydrogen injection and withdrawal cause temporal changes in pore pressure, which may lead to cyclic geomechanical stresses in both reservoir and caprock units. According to Heinemann *et al.* (2021), such cyclic stresses may result in fatigue damage, microfracture propagation, pore collapse or shear reactivation along pre-existing faults, especially under conditions of elevated pressure gradients.

These processes can reduce storage integrity by altering permeability pathways or damaging wellbore seals. Localized compaction of the reservoir may lead to caprock bending and fracture, resulting in potential hydrogen leakage into overlying formations (Kumar *et al.*, 2023). In addition, mechanical deformation may affect petrophysical properties (*e.g.*, porosity, permeability), thereby altering injectivity, recovery efficiency and containment security.

Advanced geomechanical modelling and monitoring are therefore crucial to predict and mitigate these risks. Consideration must be given to rock strength, fracture pressure gradient, historical tectonic activity and in situ stress regimes when selecting and characterizing candidate sites.

3.4. Storage capacity

One of the critical technical criteria for the selection of underground hydrogen storage (UHS) sites is the effective storage capacity of the reservoir. This refers to the total volume of hydrogen that can be injected and stored under safe operational conditions, without compromising caprock integrity, injectivity or environmental safety. Storage capacity depends on several factors, including porosity, thickness, areal extent of the reservoir, residual water saturation, and operational pressure range (Uliasz-Misiak and Misiak, 2024).

According to Uliasz-Misiak and Misiak (2024), the storage capacity for hydrogen is typically lower than that for CO₂ due to hydrogen's low density and compressibility. Furthermore, large storage formations may require significant volumes of “cushion gas” – permanently retained in the reservoir – to maintain pressure and ensure the performance of cyclic injection–withdrawal operations. Diamantakis *et al.* (2024) recommend that storage systems be limited to capacities below 120 TWh to avoid excessive operational costs associated with “cushion gas” and compression infrastructure.

Capacities may range from a few to several hundred million m³ depending on geological conditions. According to Raad *et al.* (2022), deep saline aquifers offer potentially higher storage capacity compared to depleted hydrocarbon fields, due to their

broader areal extent and thickness. However, site-specific evaluations must be conducted to ensure injectivity and seal effectiveness are not compromised.

3.5. Storage integrity

UHS projects in deep saline aquifers may face several challenges related to the potential hydrogen leakage and loss through undetected faults and geochemical and microbial reactions, including the interaction of hydrogen with minerals in the reservoir rocks (Zivar *et al.*, 2021). Storage integrity refers to the ability of the subsurface system to contain injected hydrogen safely and effectively throughout its operational lifetime. This encompasses three main risk domains: geochemical reactivity, microbial activity, and geomechanical stability (Heinemann *et al.*, 2021; Braid *et al.*, 2024).

3.5.1. Geochemical effects

Hydrogen can react with minerals present in the reservoir and caprock, particularly iron-bearing or redox-sensitive minerals. These interactions may lead to mineral precipitation or dissolution, affecting porosity and permeability, and potentially compromising reservoir performance or seal integrity (Braid *et al.*, 2024).

According to Fuentes and Santos (2023) the presence of CO₂, SO₄²⁻, Fe³⁺, clay minerals (such as kaolinite, smectite, illite) and feldspar can greatly impact hydrogen storage. Such reactions may produce undesired by-products such as H₂S or CH₄, which can contaminate the stored gas or pose surface processing challenges (Fuentes and Santos, 2023). Additionally, the presence of CO₂ as “cushion gas” in deep saline aquifers can trigger methanogenic and acetogenic reactions, converting hydrogen into methane, and causing losses of injected hydrogen.

3.5.2. Microbial activity

Microbial activity (Fig. 4) may also pose challenges for hydrogen storage in aquifers. The extent of microbial activity depends on in situ conditions such as temperature, pressure, pH and salinity. At temperatures below 80 °C and moderate salinities, microbial activity can be significant unless the storage formation is sterilized or naturally sterile due to, for instance, past burial diagenesis and or thermal maturation (Muhammed *et al.*, 2022). When the conditions are propitious for microbial activity development, different classes of microorganisms (methanogenesis, sulfate-reducers, homo-acetogenic bacteria and iron (III) reducing bacteria) can dictate hydrogen conversion and subsequent consumption and loss (Raad *et al.*, 2022).

3.5.3. Geomechanical effects

Cyclic injection and withdrawal operations in underground hydrogen storage (UHS) induce repeated pore pressure variations that can significantly impact the geomechanical stability of the storage complex (Fig. 5). These pressure fluctuations alter the in-situ stress regime, affecting both reservoir and caprock integrity. Resulting geomechanical responses may include reservoir compaction, caprock flexure, fault reactivation, microfracturing, and potential subsidence (Heinemann *et al.*, 2021; Kumar *et al.*, 2023).

Heinemann *et al.* (2021) emphasize that these cyclic operations influence both intact rock and fault behaviour through complex stress-strain-sorption interactions, as well as chemical

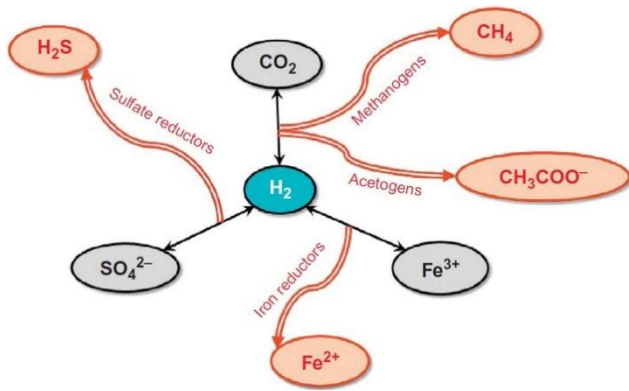


Figure 4. Potential bacterial actions that can dictate the conversion, consumption and loss of stored hydrogen in saline aquifers (Muhammed *et al.*, 2022).

Figura 4. Potenciais ações bacterianas que podem ditar a conversão, consumo e perda do hidrogênio armazenado em aquíferos salinos (Muhammed *et al.*, 2022).

interactions between hydrogen and rock minerals. Stress changes are not confined to the hydrogen or cushion gas plume; they may propagate into surrounding formations, leading to deformation beyond the pressure-affected zone.

Reservoir compaction, in particular, can reduce porosity and permeability, impairing injectivity and recovery efficiency. Moreover, such compaction may induce flexure in the overlying caprock, which could initiate fractures and create potential leakage pathways. Faults and fractures may become reactivated under repeated stress cycling, increasing the risk of induced seismicity and compromising containment security.

According to Kumar *et al.* (2023), detailed geomechanical modelling is required to evaluate these risks, particularly near the wellbore and along pre-existing faults. Such models should account for rock stiffness, fault frictional properties, and the historical evolution of the stress field. Reservoirs characterized by low stiffness, high natural fracture density, or weak sealing formations are especially susceptible to mechanical failure and leakage.

4. Non-technical requirements for underground hydrogen storage in deep saline aquifers

Other relevant aspects when selecting areas for hydrogen storage are the non-technical requirements, mainly divided into economic, health, safety and environmental (HSE) and social criteria (Nemati *et al.*, 2020). Several non-technical disqualifying requirements for UHS are presented in table 2 and discussed in more detail in the next sections.

4.1. Economic

The economic aspects inherent in UHS are important for ensuring the financial viability and long-term sustainability of a project. Several parameters are pointed out as relevant when selecting areas for the implementation of UHS projects in deep saline aquifers. According to Harati *et al.* (2024) and Hematpur *et al.* (2023), the most important aspects to consider are: (a) the volume of “cushion gas”, (b) the storage location, (c) the distance between supply and demand, (d) access to renewable energy systems, (e) labour costs, and (f) the availability of infrastructure. However, the latter is more relevant to address in the context of hydrogen storage in depleted oil and gas fields, as one can simply convert hydrocarbon exploration infrastructure into a UHS project, greatly reducing the costs of its implementation.

- “Cushion gas” volume** - is the amount of hydrogen (or any other gas) that is permanently stored in the reservoir to support the reservoir pressure and the required injection/recovery rates. It is by far an important cost factor for storing hydrogen into a reservoir and, therefore, a crucial economical criterion for selecting areas for storage purposes.
- Location** - is a criterion that is simply binary in nature, determining whether the reservoir is onshore or offshore. This consideration is essential as onshore hydrogen storage is likely to be cheaper and technically easier to implement than offshore. In this context, onshore means that the storage facility has a better connection to the local grid, to enable the efficient storage and transportation of hydrogen. Offshore,

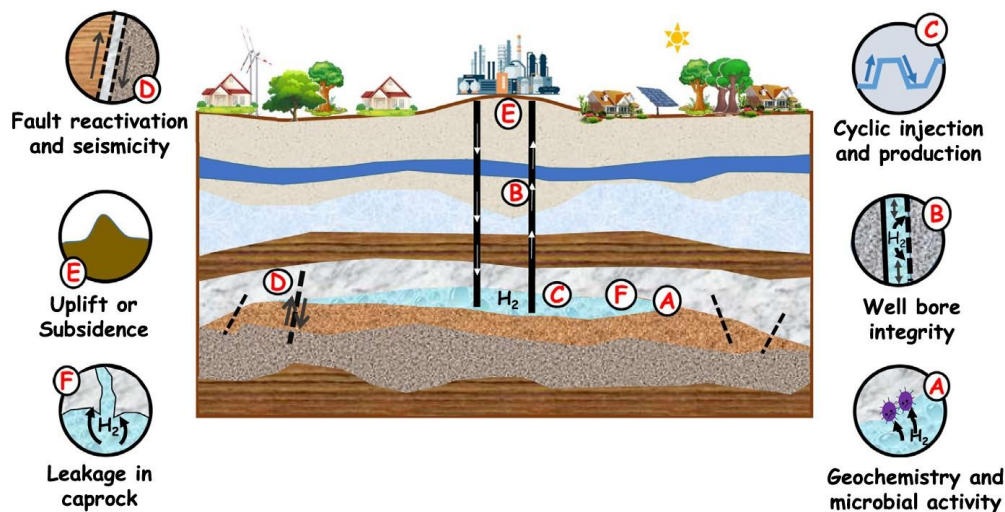


Figure 5. Main geomechanical effects (D, E and F) resulting from underground hydrogen storage (Kumar *et al.*, 2023).

Figura 5. Principais efeitos geomecânicos (D, E e F) decorrentes do armazenamento subterrâneo de hidrogênio (Kumar *et al.*, 2023).

on the other hand, means that the storage site may not have such a connection and often requires long-distance transportation, requiring additional costs.

- c) **Distance between demand and supply** - UHS economics does not depend only on storage costs, but also on the advantages of its location. Potential storage areas for hydrogen should be located closer to production facilities and areas with high demand, minimizing transport and distribution costs.
- d) **Access to renewable energy systems** - renewable energy systems are an important factor in the selection of suitable areas. They can affect the economic viability and sustainability of a UHS project. The distance of the storage site to the location of renewable energy systems can reduce the cost and carbon footprint of hydrogen production, transport and distribution. It can also reduce the impact of integrating and optimizing renewable energy systems, as the stored hydrogen volumes can also be used to balance their intermittency and support energy grid stability.
- e) **Labor costs** - refers to the human resources and costs associated with the UHS projects. Some authors tend to consider it a social factor because it is also closed related to the job creation.
- f) **Availability of infrastructure** – defined as the availability of existing legacy infrastructure and the potential costs reduction for the storage site development. As previously mentioned, the existing storage facilities from depleted hydrocarbon fields can be re-purposed for UHS projects.

4.2. Health, safety and environment

The criteria to be considered when selecting areas for hydrogen storage include regional, environmental and public risks, and legal restrictions. Key aspects to be considered are the following:

- a) **Regional risks** - the likelihood of natural disasters, such as earthquakes, occurring where UHS projects are implemented can lead to additional costs and potential leakage risks.
- b) **Environment and public** - UHS projects must be based on comprehensive evaluation and prediction assessments so that any risk is minimized, to guarantee minimum environment and public impacts during the storage operations.
- c) **Legal restrictions** - before any UHS project can be implemented, the required legal challenges must be addressed.

4.3. Social

Regarding social requirements, several authors point out two aspects that need to be guaranteed when selecting areas for hydrogen storage, namely social acceptance and job creation.

Before developing a UHS project, all residents and the communities must be consulted. UHS projects can only be implemented with local acceptance (Hematpur *et al.*, 2023). On the other hand, job creation refers to all direct and indirect jobs created with the implementation of a UHS and infrastructure project and its effects on the local economy of the area.

In summary of this work, table 3 is presented to underline the importance of various parameters in site characterization and selection for UHS in geological formations in terms of storage capacity, performance and location of suitable storage sites

(Bouteldja *et al.*, 2021). The relevance of the set of parameters listed in table 3 to these three factors was conducted based on a numerical classification, in which classification equal to 1 represents a lower importance/ impact, while classification equal to three represents a critical importance/ impact for the UHS site selection.

Table 3. Selection thresholds for hydrogen storage sites (Bouteldja *et al.*, 2021).

Tabela 3. Limiares de desqualificação técnica e não técnica para o armazenamento subterrâneo de hidrogénio (Bouteldja *et al.*, 2021).

Parameters	Capacity	Performance	Location
Depth	2	1	N/A
Net-thickness	2	2	N/A
Area	3	1	N/A
Trap type	3	1	N/A
Trap closure	3	3	N/A
Depositional environment	3	3	N/A
Effective porosity	2	1	N/A
Permeability	N/A	2	N/A
Rock types & mineralogy	N/A	1	N/A
Main faults and continuities	2	2	N/A
Connectivity (fault networks, fractures, compartmentalization)	N/A	2	N/A
In-situ fluids	2	2	N/A
Initial pore pressure	1	1	N/A
Fluid temperature	1	1	N/A
Type of aquifer and hydrogeological activity	3	3	N/A
In-situ fluid density	1	1	N/A
In-situ fluid viscosity	1	1	N/A
Initial and current fluid contacts	1	1	N/A
Production history	2	2	N/A
Overlying strata	N/A	N/A	2
Overlying aquifers	N/A	N/A	2
Seismicity	N/A	N/A	3
Accessibility	N/A	N/A	2
Subsidence	N/A	N/A	2
Land ownership	N/A	N/A	3
Mining rights, regulatory compliance	N/A	N/A	3
Acceptability	N/A	N/A	3

5. Screening framework for hydrogen storage in saline aquifers

The safe and efficient deployment of underground hydrogen storage (UHS) in deep saline aquifers requires the integration of diverse technical and non-technical criteria. These criteria encompass geological, geochemical, geomechanical, and operational aspects that must be systematically evaluated in a site-specific manner. While each storage site presents unique characteristics, the discussion below synthesizes the key considerations that have emerged from previous sections and proposes a high-level screening framework to support early-stage project development.

5.1. Integrated criteria and trade-offs

The analysis of reservoir properties indicates that porosity (> 15% – 20%) and permeability (> 50 – 500 mD) are minimum thresholds for ensuring injectivity and effective deliverability of hydrogen. However, these petrophysical parameters must be contextualized within the broader depositional framework of the aquifer. Massive, homogeneous sandstone units with laterally continuous flow units are preferred, as they reduce heterogeneity-related inefficiencies and simplify plume evolution modelling (Tarkowski and Uliasz-Misiak, 2022; Raad *et al.*, 2022).

Caprock performance is equally critical. Effective seals should be thick (> 50 m), laterally extensive, and composed of low-permeability, chemically inert lithologies such as halite, anhydrite, or well-compacted shales (Bai *et al.*, 2014; Diamantakis *et al.*, 2024). Furthermore, caprock integrity must be verified against molecular diffusion risks and cyclic geomechanical effects associated with hydrogen injection and withdrawal. Geomechanical modelling should address fault reactivation, fracture pressure gradients, and stress cycling in both reservoir and seal (Kumar *et al.*, 2023).

Geochemical and microbiological factors, though sometimes underestimated in early screening, can profoundly influence storage integrity. Hydrogen-consuming microbial populations (*e.g.*, sulfate-reducing bacteria and methanogens) may thrive under suitable subsurface conditions, leading to gas losses and generation of undesired by-products (Raad *et al.*, 2022; Muhammed *et al.*, 2022). Similarly, mineralogical incompatibilities may result in porosity loss or seal weakening. These processes highlight the importance of laboratory reactivity experiments and microbiological assessments during pre-operational site characterization.

In terms of structural setting, tectonic stability is paramount. Anticlines and fault-bounded traps with intact sealing elements are desirable, but fault permeability must be carefully evaluated. Sites located in tectonically quiescent basins with a well-defined stress regime and minimal seismic activity offer a lower risk of geomechanical failure (Fuentes and Santos, 2023; Miodic *et al.*, 2023).

Operational considerations such as reservoir depth (ideally 800 – 2000 m), pressure regime, temperature, and infrastructure proximity also play a decisive role. Shallower sites may present microbial risks and insufficient containment pressure, while deeper sites may suffer from reduced permeability and increased costs (Jahanbakhsh *et al.*, 2024; Uliasz-Misiak and Misiak, 2024). Thus, optimal depth–thickness–injectivity combinations should be sought based on regional geological context.

5.2. Conceptual screening approach

Based on the integration of the above criteria, a conceptual framework for the preliminary screening of UHS sites in deep saline aquifers is proposed. This framework involves a multi-step, hierarchical approach:

- 1) Basin-level assessment: identify sedimentary basins with tectonic stability, aquifer-caprock pairs, and sufficient data availability (geological, seismic, well logs).
- 2) Structural and stratigraphic analysis: delineate traps with sufficient closure, assess seal continuity, fault architecture, and proximity to renewable energy hubs or hydrogen corridors.

- 3) Reservoir quality screening: evaluate porosity, permeability, facies distribution, thickness, and hydraulic properties using existing logs and core data.
- 4) Caprock performance screening: characterize mineralogy, permeability, geochemical stability, thickness, and potential for diffusive leakage.
- 5) Geochemical and microbial risk assessment: analyse rock-fluid compatibility, microbial community profiles, and potential for hydrogen loss or transformation.
- 6) Geomechanical evaluation: model pressure cycling, stress redistribution, fracture reactivation, and mechanical integrity of caprock and faults.
- 7) Storage capacity estimation: calculate theoretical and effective hydrogen capacity considering cushion gas, injectivity limits, and operational range.
- 8) Risk and feasibility matrix: integrate findings into a multi-criteria decision matrix with scoring or ranking schemes, enabling prioritization of candidate sites.

This systematic approach does not aim to replace detailed site-specific feasibility studies but serves as a decision-support tool for early-stage evaluation, enabling the selection of promising sites for more detailed modelling and experimental work.

9. Final remarks

The global shift toward low-carbon energy systems necessitates the development of scalable and long-duration energy storage technologies. UHS in deep saline aquifers offers a geographically extensive and technically feasible solution to support seasonal energy balancing and the decarbonization of hard-to-electrify sectors. However, its implementation poses multidisciplinary challenges that require rigorous scientific, technical, and regulatory evaluation.

This study provides an integrated assessment of the key geological, geochemical, geomechanical, and operational criteria that govern the suitability of deep saline aquifers for hydrogen storage. The findings highlight that site viability depends on the dynamic interplay among reservoir quality, caprock integrity, structural complexity, and potential geochemical or microbial interactions. In particular, cyclic injection and withdrawal operations introduce geomechanical stresses that must be carefully characterized and modelled to preserve long-term containment integrity.

To address these complexities, a structured, multi-criteria screening framework has been presented, emphasizing basin-scale geological context, data availability, and risk-based prioritization. While the framework is broadly applicable, its effectiveness depends on the availability of high-resolution subsurface data, interdisciplinary collaboration, and iterative validation through field-scale demonstration projects.

Currently, there is a lack of commercial-scale projects on pure hydrogen storage implemented in deep saline aquifers. The benchmarking requirements presented in this article and the broad site screening framework resulted from the experience and data reported in the literature from other subsurface storage projects. In addition, this work aims to provide broad insights of the technical and non-technical criteria for characterization, selection and implementation of UHS projects, including those in which the stored hydrogen is mixed with other gases. Specific standards, guidelines and regulatory frameworks are also still lacking, strictly for pure hydrogen storage operations in deep saline aquifers or other geological environments.

Despite growing interest and research efforts, substantial knowledge gaps persist – especially concerning the long-term fate and behaviour of hydrogen in porous geological media. Standardized protocols for site screening, performance monitoring, and regulatory compliance are still under development. Lessons from CO₂ and natural gas storage provide a valuable foundation, but the unique physico-chemical properties of hydrogen require tailored approaches.

In summary, UHS in deep saline aquifers presents a technically viable yet complex solution for large-scale energy storage. By advancing integrated screening methodologies and addressing current knowledge gaps, the energy sector can accelerate the deployment of safe and effective underground hydrogen storage systems, supporting broader energy transition and decarbonization objectives.

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