International Journal of Hydrogen Energy 149 (2025) 150110

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

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

Underground hydrogen storage suitability index: A geological tool for evaluating and ranking storage sites

Lorenzo Borghini [a,*], Amerigo Corradetti [a], Anna Del Ben [a], Marco Franceschi [a], Lorenzo Bonini [a,b]

[a] Department of Mathematics, Informatics and Geosciences, University of Trieste, Via Weiss, 2, 34128, Trieste, Italy
[b] Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy

A R T I C L E I N F O

Keywords:
Underground hydrogen storage
Suitability index
Site selection
Site ranking
Site screening

A B S T R A C T

Underground Hydrogen Storage (UHS) is a promising solution to maximize the use of hydrogen as an energy carrier. This study presents a standardized methodology for assessing UHS quality by introducing the Underground Hydrogen Storage Suitability Index (UHSSI), which integrates three sub-indices: the Caprock Potential Index (CPI), the Reservoir Quality Index (RQI), and the Site Potential Index (SPI). Parameters such as porosity, permeability, lithology, caprock thickness, depth, temperature, and salinity are evaluated and ranked from 0 (unsuitable) to 5 (excellent). The methodology was validated using data from six worldwide sites, including salt caverns and aquifers. Sites like Moss Bluff, Clemens Dome, and Spindletop (USA) scored highly, while Teesside (UK), Lobodice (Czech Republic), and Beynes (France) were classified as unsuitable due to shallow depths and microbial activity. A software tool, the UHSSI Calculator, was developed to automate site evaluations. This approach offers a cost-effective tool for preliminary screening and supports the safer development of UHS.

1. Introduction

Hydrogen is attracting increasing interest in the scientific community, private sector, and governmental bodies due to its potential as a viable alternative to fossil fuels, opening perspectives to mitigate global warming. The natural occurrence of pure hydrogen (known as 'white hydrogen') [1] is rare, likely primarily linked to serpentinization processes ([121]; [2–4]). Hydrogen can be produced through a process known as water electrolysis, where electricity is used to split water molecules, separating hydrogen from oxygen [5,6]. Electrolysis can be powered either by the combustion of fossil fuels or by renewable sources such as solar, wind, and hydroelectric energy. These renewable energy sources offer the advantage of being carbon dioxide-free and abundantly available [7–9]. Hydrogen derived from renewable energy sources is known as 'green hydrogen' (Fig. 1) and currently makes up only a small fraction of the total global hydrogen production [10–12]. Nevertheless, cost trends indicate that the price of green hydrogen production will become more competitive than hydrogen generated through fossil fuels within the next decade [13,14].

Despite the numerous environmental benefits of green hydrogen, the seasonality and intermittency of electricity produced from renewable energy sources pose a significant challenge [15–17]. To tackle it, it is essential to store surplus hydrogen generated during peak production periods [17–19]. Storage in batteries presents drawbacks and poses environmental, geopolitical, and technical issues [20–22]. An alternative method that could allow storage of high volumes of hydrogen to be used at need is underground storage of gaseous hydrogen (Fig. 1) [13, 18,19,23]. An efficient storage system must ensure resource availability when needed, adapting to varying demand timescales by distributing generated energy across hourly, daily, and seasonal periods [10]. Subsequently, hydrogen can be utilized as needed by converting it back into electricity through fuel cells [24–26].

Compared to other large-scale storage options on the surface, Underground Hydrogen Storage (UHS) offers several advantages, including lower investment costs, higher safety standards, reduced surface footprint, and minimal environmental impact (Fig. 1) [18,19,27,28]. UHS options generally fall into two main categories: i) porous geological formations, which include depleted hydrocarbon reservoirs and deep saline aquifers, and ii) artificially solution-mined cavities within salt formations, often referred to as salt caverns. As of today, active or completed UHS pilot projects have never used 100 % pure hydrogen, but mixtures with other gases ([19] and references therein).

* Corresponding author. Department of Mathematics, Informatics and Geosciences, University of Trieste, Via Weiss 2, 34128, Trieste, Italy.
E-mail address: lorenzo.borghini@phd.units.it (L. Borghini).

https://doi.org/10.1016/j.ijhydene.2025.150110
Received 28 April 2025; Received in revised form 3 June 2025; Accepted 19 June 2025
Available online 24 June 2025

UHS is influenced by multiple mechanisms, including geochemical, biochemical, and hydrodynamic interactions that can occur in the reservoir (Fig. 2) [29]. One of the most important mechanisms, the structural trapping capacity of the caprock, strongly depends on capillary pressure which is the force required for a non-wettable fluid to displace a wettable fluid from capillaries [30–32]. This pressure is affected by the rock-fluid interfacial tension and the wetting properties of the fluid under investigation. In the presence of brine in the reservoir, hydrogen behaves as a non-wetting phase [33]. Furthermore, capillary pressure plays a crucial role in determining the recovery factor, which is defined as the ratio between the amount of hydrogen successfully recovered and the total amount initially stored in the reservoir. In scenarios where capillary pressure of the reservoir rock is at its lowest, the recovery factor is at its highest [34–37]. Capillary pressure is key to understanding the behavior of hydrogen during the displacement of reservoir fluid [36]; however, this phenomenon in UHS is yet to be fully understood. Hysteresis also plays an important role. The hysteresis effect is where a certain amount of gas remains trapped in the reservoir pores during the withdrawal phase [38,39]. Hysteresis exhibits variable effects related to the number of injection-withdrawal cycles. As the number of cycles increases, the hysteresis tends to decrease, leading to a progressive increase in the recovery factor over time [40–42]. The reservoir rock needs to have high porosity, as observations indicate that during hydrogen injection-withdrawal cycles, increased pressure and temperature lead to a decrease in porosity, following the Burger creep model [43–45]. This reduction in porosity consequently results in lower storage capacity and decreased injection-withdrawal efficiency. However, evidence suggests that porosity can increase under certain conditions, such as in carbonate reservoirs where the use of CO_2 as a cushion gas has been shown to enhance porosity [46]. Moreover, in UHS, fingering can occur when hydrogen is injected into a porous medium saturated with brine or a denser gas, leading to irregular flow patterns and potential inefficiencies in storage and recovery. Segregation refers to the vertical and lateral separation of hydrogen from other fluids due to differences in density and buoyancy (Fig. 2) [17].

Geochemical reactions associated with hydrogen storage can be categorized as biotic and abiotic (Fig. 2) [47–49] and can influence both caprock and reservoir characteristics, leading to variations in mineralogical composition and potential losses of stored hydrogen. Here, *loss of hydrogen* does not refer solely to leakage from the reservoir but also includes its conversion into other gases through microbial or geochemical reactions, as well as its reduction in mobility [50–56]. Recent studies have shown that as the Total Organic Carbon (TOC) content increases in the shale caprock, the interfacial tension between the rock and H_2 decreases. This results in enhanced wettability of hydrogen gas, potentially facilitating its escape through the caprock [30, 57]. Several studies suggest that sandstone reservoirs generally outperform carbonate reservoirs ([29], and references therein [53]). However, research on the impact of hydrogen on carbonate reservoirs presents conflicting results. Some studies indicate that calcite in contact with hydrogen can undergo a significant reduction in porosity [50], while others report that this reaction has little to no effect on porosity [51]. The suitability for UHS of sandstone reservoirs can be influenced by the clay mineral content as the wettability of clay changes with temperature, leading to hydrogen loss [58]. Abiotic reactions may also involve iron-bearing minerals like pyrite and hematite, which can react with hydrogen to form new mineral precipitates [41,59–61]. Although this effect may seem negligible in the short term, the reaction rate can accelerate over a year, causing a considerable increase in mineral precipitates [62,63]. Mineral precipitation induces changes in the

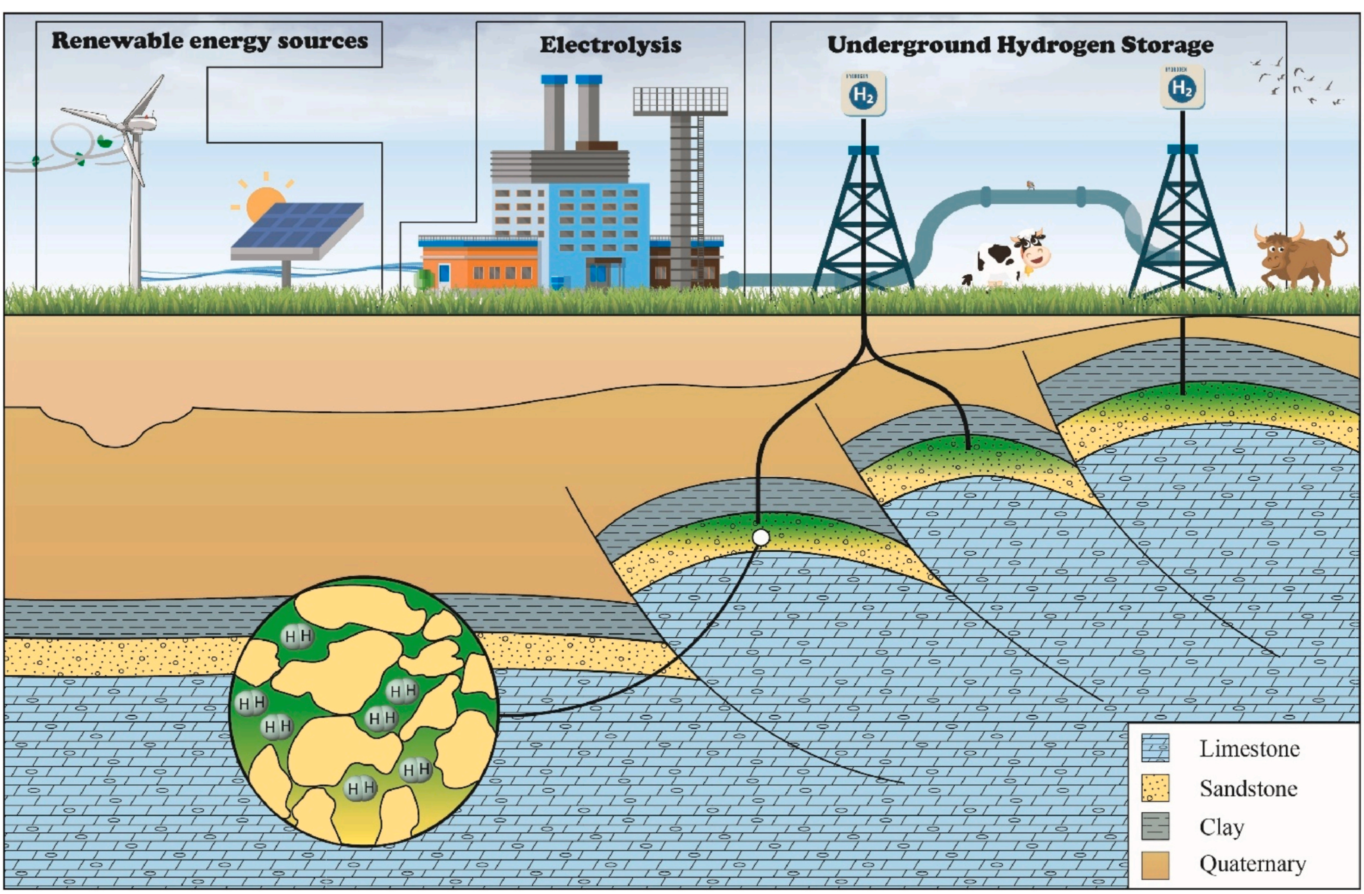

Fig. 1. A schematic representation of the green hydrogen production and storage process. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

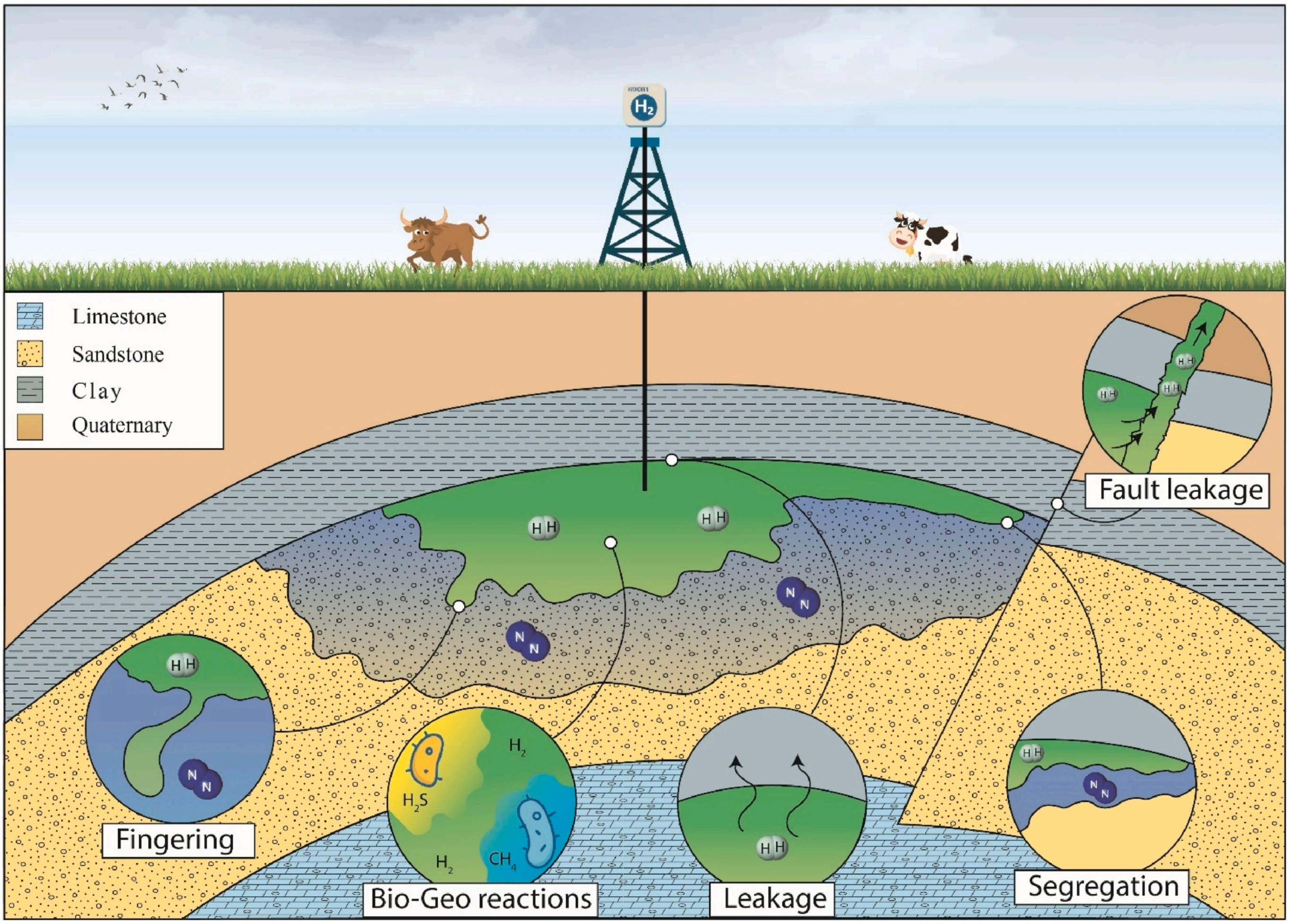

Fig. 2. Schematic representation of potential issues associated with UHS.

reservoir's hydrodynamic characteristics and hydrogen loss. Extra caution must be taken when converting a depleted gas field into a hydrogen storage site, as the presence of previously stored fuels may alter the hydraulic properties of the rock, such as wettability and relative permeability. Furthermore, in converted sites, existing infrastructure may not be suitable for UHS due to the potential embrittlement of steel caused by hydrogen exposure. ([64]; [119] [65]).

In UHS, biotic reactions involve microorganisms that can metabolize hydrogen. Methanogenesis, homoacetogenesis, and sulfate reduction are the most common reactions described in recent work (Fig. 2) [18, 47–49,66,67]. These processes may lead to alterations in the composition and a reduction in the volume of the stored hydrogen [56,68–71]. Additionally, most microorganisms in nature grow in biofilms attached to surfaces, and even small amounts of biofilm can alter reservoir properties by reducing pore throat sizes, increasing flow-path tortuosity, and modifying wettability. These changes can impact hydrogen mobility and storage efficiency [49,72,73].

Currently, several active UHS sites exist worldwide, most of which are utilized for industrial purposes, while only a few dedicated to research ([23,74]; [119] [41]) (Fig. 3). Most of them are in salt caverns and the volumes stored do not exceed 750,000 m^3 ([41] and references therein). The oldest storage site is Ketzin in Germany, where town gas (about 62 % H_2) was stored from 1960 to 2000 at a depth from 250 to 400 m [75,76]. However, between 1964 and 1985, a reduction in gas volume was reported, primarily attributed to chemical and microbiological reactions within the reservoir [67,76,77].

As scientific research on hydrogen progresses, authorities around the world are actively identifying suitable storage sites within their territories to assess their overall long-term storage capacity (e.g., Ref. [22,27,78–80]). For example, Barison et al. [81] estimated that the potential hydrogen static volume in Italy is 69.2 TWh based on existing underground gas stores. Lackey et al. [82] estimate that the underground geological storage facilities in the United States (U.S.) can hold up to 327 TWh (9.8 MMT) of pure hydrogen. Peecock et al. [83] estimate a total hydrogen storage capacity of 3454 TWh in the UK offshore hydrocarbon fields. Tarkowski et al. [84] estimated that 514 salt caverns or nine salt aquifers are needed to meet the estimated maximum hydrogen demand in Poland (38.1 TWh). Caglayan et al. [85] estimated that the total technical H_2 storage potential in salt caverns across Europe is 84.8 PWh, with Germany having the highest storage potential at 9.4 PWh.

Currently, few papers have discussed methodologies for selecting hydrogen storage sites (e.g., Ref. [86–88]; [120]; [65,89,90]). As of 2023, only 4 % of all published material about UHS was dedicated to research on site selection [41], and yet there is not widely accepted and standardized procedure for screening or ranking reservoirs for UHS, whether they are aquifers or depleted hydrocarbon fields, to assess their prolonged suitability [81]. Indeed, studies on site selection employ various methodologies to evaluate storage sites, making the results impossible to compare. Therefore, a single, uniform method for selecting UHS sites is needed.

In this study, we present a standardized method for classifying UHS sites and rank them. The evaluation relies on assessing caprock, reservoir, and site conditions using a set of parameters with established thresholds. For the caprock, we considered porosity, lithology, and thickness. For the reservoir, we included porosity and permeability. For the site, temperature, salinity (NaCl, M), and depth are considered.

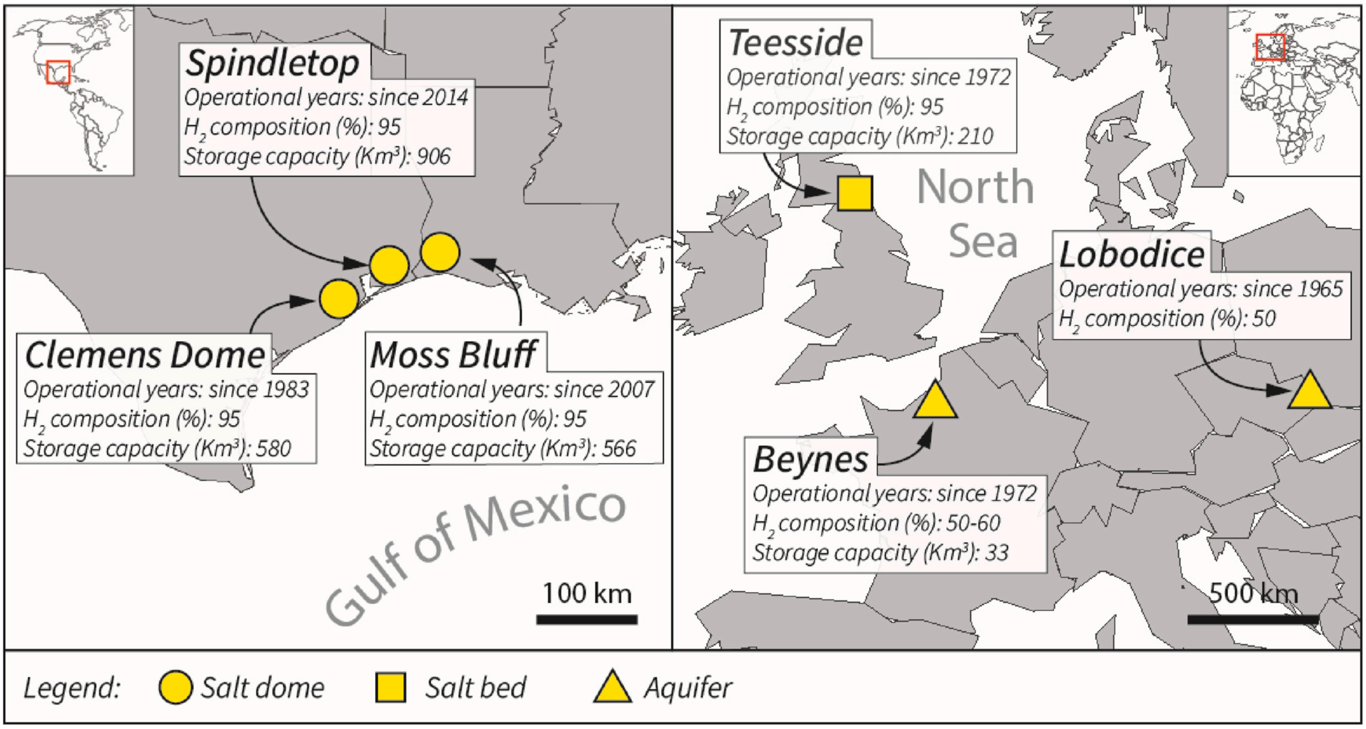

Fig. 3. The operating UHS facilities worldwide.

Subsequently, hydrogen storage sites are prioritized using a scoring system based on the quality of each parameter considered. The proposed method was validated by applying it to six hydrogen storage sites worldwide (Fig. 3), including four salt caverns and two salt aquifers, demonstrating its effectiveness, and providing significant insights into the suitability of these sites for UHS.

2. Development of the UHS suitability index framework

The development of a scoring method for site suitability requires certain initial conditions to be met. Specifically, the presence of a trap, either stratigraphic or structural, is essential, as it works in combination with caprock and reservoir properties to ensure effective hydrogen containment.

The proposed methodology does not account for pressure evolution during site operations. The caprock is assumed to be undeformable, and potential failures or deformations resulting from pressure increases or fluctuations are not considered.

This study considers intrinsic permeability instead of relative permeability because intrinsic permeability is more commonly available and widely reported in reservoir studies, whereas relative permeability depends on the specific fluid present in the reservoir rock, making it less suitable for cross-comparison among sites with different fluid compositions. However, for a thorough assessment of a specific site, measuring relative permeability is recommended to obtain a more accurate understanding of fluid flow behavior. Permeability is the primary petrophysical parameter controlling hydrogen flow in the reservoir, while diffusivity has a relatively minor impact [91]. Diffusivity results in a significant loss of hydrogen during the initial phase of rock saturation, followed by a decline in the diffusion rate at saturation [91]. Consequently, this study emphasizes the permeability of the caprock and reservoir over diffusivity, which is omitted from this ranking scheme.

In this study, hydrogen saturation is not considered. However, this parameter will be included in the future, as it is crucial in determining not only permeability but also wettability and capillarity, all of which play a fundamental role in the effectiveness of underground hydrogen storage.

As stated in the introduction, carbonate reservoirs or those with a high clay mineral content are deemed unsuitable for UHS. Hence, reservoirs that are predominantly composed of carbonates or have a significant clay content are excluded a priori [50,58].

The proposed approach considers the total storable volume of hydrogen solely from an economic perspective, without taking into account its implications for the geological feasibility of storage. As this is a first approach to UHS site selection, the method assumes the presence of petrophysical heterogeneity in both the reservoir and the caprock, which is considered the most favorable condition for effective hydrogen storage [29].

Unlike CO_2 storage, the upper depth limit for hydrogen storage is not constrained by physical properties but rather by the risk of contaminating shallow aquifers. For this reason, in this study, only sites at depths greater than 800 m are considered suitable. This topic will be specifically addressed in Section 2.1.3.

Hydrogen storage is still in its early stages; therefore, drawing on insights from natural gas storage provides an alternative approach likely applicable to UHS, at least in the preliminary site selection phase.

With the previous conditions met, the here proposed UHS site ranking method considers three key aspects: i) the caprock, ii) the reservoir, and iii) the site itself, which are used to compute a UHS Suitability Index (UHS_{SI}).

2.1. Parameters of the UHS suitability index

The Underground Hydrogen Storage Suitability Index (UHS_{SI}) is a comprehensive measure encompassing three distinct components of underground hydrogen storage: the caprocks (Caprock Potential Index, CPI), the reservoirs (Reservoir Quality Index, RQI), and the sites (Site Potential Index, SPI). Each parameter evaluated in this method is normalized based on thresholds ranging from 0 to 5, where 5 represents the best score. These normalized parameters are referred to as Rank (for instance, K_{Rank} is the normalized permeability, or CPI_{Rank} is the normalized Caprock Potential Index), and the normalizations of parameters can be derived from related tables (Tables 1–3). In cases where specific parameter data are unavailable, a default rank of 1 is assigned.

Table 1
Parameters, thresholds, and Ranking for the Hydrogen Caprock Potential Index (H_2 CPI). Where ϕ is the porosity, CT is the Caprock thickness, and Lit is the lithology.

Porosity (%)	ϕ Rank	Lithology	Lit Rank	Caprock thickness (m)	CT Rank	H_2 CPI	H_2 CPI Rank	Description
$\phi > 5$	0	Other lithology	0	$CT \leq 30.0$	0	CPI <0.04	0	Very poor
$4{,}5 < \phi \leq 5$	1	V. Coarse silt/Marl	1	$30.0 < CT \leq 50.5$	1	$0.04 \leq$ CPI <0.32	1	Poor
$4 < \phi \leq 4{,}5$	2	Medium/coarse silt	2	$50.5 < CT \leq 71.0$	2	$0.32 \leq$ CPI <1.08	2	Fair
$3{,}5 < \phi \leq 4$	3	V. Fine/fine silt	3	$71.0 < CT \leq 91.5$	3	$1.08 \leq$ CPI <2.56	3	Good
$3 < \phi \leq 3{,}5$	4	Clay/Shale	4	$91.5 < CT \leq 112.0$	4	$2.56 \leq$ CPI <5.0	4	Very good
$\phi \leq 3$	5	Salt	5	$CT > 112.0$	5	CPI $\geq$5.0	5	Excellent

Table 2
Parameters, thresholds, and ranking for the H_2 Reservoir Quality Index (H_2 RQI). Where Φ is the porosity, k is the intrinsic permeability.

Porosity (%)	Φ Rank	Permeability (mD)	k Rank	H_2 RQI	H_2 RQI Rank	Description
$\phi \leq 10$	0	$k \leq 500$	0	RQI $\leq$0.22	0	Very poor
$10 < \phi \leq 14.5$	1	$500 < k \leq 1375$	1	$0.22 <$ RQI $\leq$0.44	1	Poor
$14.5 < \phi \leq 19$	2	$1375 < k \leq 2250$	2	$0.44 <$ RQI $\leq$0.64	2	Fair
$19 < \phi \leq 23.5$	3	$2250 < k \leq 3125$	3	$0.64 <$ RQI $\leq$0.85	3	Good
$23.5 < \phi \leq 28.0$	4	$3125 < k \leq 4000$	4	$0.85 <$ RQI $\leq$1.05	4	Very good
$\phi > 28.0$	5	$k > 4000$	5	RQI >1.05	5	Excellent

This conservative approach is intended to reflect a cautious evaluation, avoiding overestimation of site suitability in the absence of reliable information. A rank of 1 ensures that data gaps do not artificially inflate the UHSSI score, while still allowing the site to be evaluated and compared. This threshold was chosen as a balance between penalizing uncertainty and maintaining inclusiveness in the screening process.

In the following section, a comprehensive compilation of parameters used in the classification tables and the equations developed for the UHS_{SI} is provided for each sub-index. The values assigned to individual parameters are derived from an extensive review of the existing literature. These parameters focus on the geological aspects of UHS, as identified by Saeed and Jadhawar [29]. Therefore, this study does not consider economic and geomechanical aspects. These latter, however, cannot be neglected when selecting a site based on the UHS_{SI}. This ensures a thorough assessment of site integrity under time-varying storage pressures and economic sustainability.

2.1.1. H_2 Caprock Potential Index

A caprock is an impermeable rock layer that overlays a permeable reservoir rock. Its primary function is to seal the reservoir and prevent the leakage of hydrogen or other stored buoyant fluids. The key caprock parameters identified and contributing to H_2 CPI are (Table 1):

- Porosity (ϕ)
- Lithology (Lit)
- Caprock thickness (CT)

The H_2 Caprock Potential Index is obtained using equation (1):

$$H_2\ CPI = (\phi_{\ Rank} {}^{*}\ Lit_{\ Rank} {}^{*}\ CT_{\ Rank})\ /\ 25 \tag{1}$$

The five parameter ranks, including the H_2 CPI, range from 0 (very poor) to 5 (Excellent).

These parameters were selected for their significant impact on the caprock's ability to inhibit fluid flow. Thresholds were established based on relevant literature related to hydrogen storage, as detailed below.

2.1.1.1. Caprock porosity (ϕ). The porosity of the caprock, expressed as a percentage (%), is a parameter that describes the relationship between the volume of voids and the matrix of the sealing rock. This factor may influence the sealing capacity of the caprock and determine the potential loss of hydrogen [92,93].

Hemme and Van Berk [93] used a hydrogeochemical modeling approach with the geochemical software PHREEQC [94], assuming an initial caprock porosity of 5 %, the absence of faults, and non-reactive hydrogen. Their modeling estimated that a non-reactive tracer, with a diffusion coefficient equivalent to hydrogen (5.13×10^{-9} m^2 s^{-1}), indicated significant amounts of hydrogen (greater than 4.0×10^{-7} mol KgW^{-1}) penetrated for 4 m into the caprock (vertically) over 30 years. Their findings suggest that a porosity of 5 % represents the upper threshold for effectively preventing hydrogen leakage through the caprock.

Ghaedi et al. [92] examined hydrogen diffusion into the caprock of depleted gas reservoirs using a semi-analytical approach and Schlumberger Eclipse 300 simulator in two distinct cases. Their findings revealed that Case 1, with 10 % porosity and a diffusion coefficient of 10^{-8} m^2/s, resulted in greater H_2 loss compared to Case 2, which had 5 % porosity and a diffusion coefficient of 10^{-9} m^2/s.

Over the 30-year cyclic operation period, H_2 losses were estimated at 5.5 % for Case 1 and 1.16 % for Case 2.

A caprock porosity greater than 5 % was assigned the minimum ranking score for ϕ (Table 1).

2.1.1.2. Caprock lithology (Lit). According to Bo et al. [55], caprocks made of lithologies that do not contain calcite are considered more suitable for UHS because hydrogen tends to dissolve calcite, potentially resulting in a loss of hydrogen. However, Zeng et al. [54] demonstrated that the dissolution rates of siliceous (quartz-rich), calcareous

Table 3
H_2 Site Potential Index parameters, thresholds, and ranking. Where NaCl is the saturation of the water formation in moles and D is the depth.

H_2 Site Potential Index								
Temperature (°C)	T Rank	NaCl (M)	NaCl Rank	Depth (m)	D Rank	H_2 SPI	H_2 SPI Rank	Description
$T \leq 55{,}00$	0	$S \leq 1{,}7$	0	$D > 3700$ or $D \leq 800$	0	SPI <0,2	0	Very poor
$55{,}00 < T \leq 59{,}25$	1	$1{,}7 < S \leq 2{,}0$	1	$3200 < D \leq 3700$	1	$0{,}2 \leq$ SPI <0,8	1	Poor
$59{,}25 < T \leq 63{,}50$	2	$2{,}0 < S \leq 2{,}4$	2	$2600 < D \leq 3200$	2	$0{,}8 \leq$ SPI <1,8	2	Fair
$63{,}50 < T \leq 67{,}75$	3	$2{,}4 < S \leq 2{,}7$	3	$2000 < D \leq 2600$	3	$1{,}8 \leq$ SPI <3,2	3	Good
$67{,}65 < T \leq 72{,}00$	4	$2{,}7 < S \leq 3$	4	$1400 < D \leq 2000$	4	$3{,}2 \leq$ SPI <5,0	4	Very good
$T > 72{,}00$	5	$S > 3$	5	$800 < D \leq 1400$	5	SPI $\geq$5,0	5	Excellent

(calcite-rich), and argillaceous (illite-rich) shales remain below 1 % over a 30-year, highlighting the strong caprock integrity that supports the suitability of these formations for UHS. Nevertheless, further studies are needed to better understand the behavior of carbonate formations in UHS applications. For this reason, carbonate caprocks are excluded from consideration in this study, and siliceous or argillaceous shales are regarded as one of the most favorable caprock types. The most promising caprock for UHS is salt due to its exceptional sealing capacity [85]. Most ongoing UHS projects utilize salt caprocks ([41], and references therein), and there have been no reported instances of hydrogen leakage attributed to salt caprock failure in the literature. As a result, salt was identified as the highest-ranked caprock lithology in Table 1. Clay, shale, silt, and marl are also considered excellent caprock lithologies due to their low permeability [95], and thus, they were included in the classification table (Table 1), with their rankings adjusted according to granulometry.

2.1.1.3. Caprock thickness (CT). In gas storage, caprock thickness and gas column height are considered the main parameters to be considered to prevent gas losses [96]. A direct correlation exists between the thickness of the caprock and the maximum height of the gas column only when the caprock thickness exceeds the lower threshold, as noted by Ma et al. [96]. The effective sealing capacity of the gas column primarily depends on the sealing potential of the caprock, which is governed by its lithology and thickness. In general, the thicker the caprock, the lower the risk of leakage. In their study, Ma et al. [96] examined several natural gas storage sites and concluded that a caprock thickness of 30 m serves as the lower limit. In a more recent study Barison et al. [81] identified 30 m as the minimum thickness required for caprock to ensure adequate sealing capacity. This criterion was adopted in this work, assigning a minimum score to caprock thicknesses of 30 m.

This study considers a minimum storage depth of 800 m (see Section 2.1.3). By integrating the findings of Ma et al. [96] and Iglauer [97], the maximum height of storable H_2 at 800 m was determined to be 157 m (Fig. 5). Under these conditions, maximum sealing is achieved with a caprock thickness of at least 112 m (Fig. 4). Hence this value was considered the threshold for maximum score of this parameter in the proposed ranking (Table 1). Caprocks exceeding 112 m in thickness are deemed suitable for hydrogen storage regardless of the reservoir depth.

2.1.2. H_2 Reservoir Quality Index

Porosity and intrinsic permeability are critical factors in assessing a reservoir's potential and suitability for underground storage. The H_2 Reservoir Quality Index (H_2 RQI) serves as a key parameter for evaluating reservoirs based on their hydraulic and physical properties ([98, 99], and references therein; [100–102]). This index, which relies on both porosity and intrinsic permeability, provides a valuable framework for comparing various reservoirs and classifying them according to their flow capacity. In this study, the H_2 RQI is evaluated within a range of 0.22–1.05.

H_2 RQI is calculated through equation (2):

$$H_2\ RQI = 0.0314 * \sqrt{(k * \phi)} \tag{2}$$

where k is the intrinsic permeability in mD, and ϕ is the reservoir porosity in decimals.

The critical parameters identified for reservoir and contributing to H_2 RQI are (Table 2):

- Porosity (φ)
- Intrinsic Permeability (k)

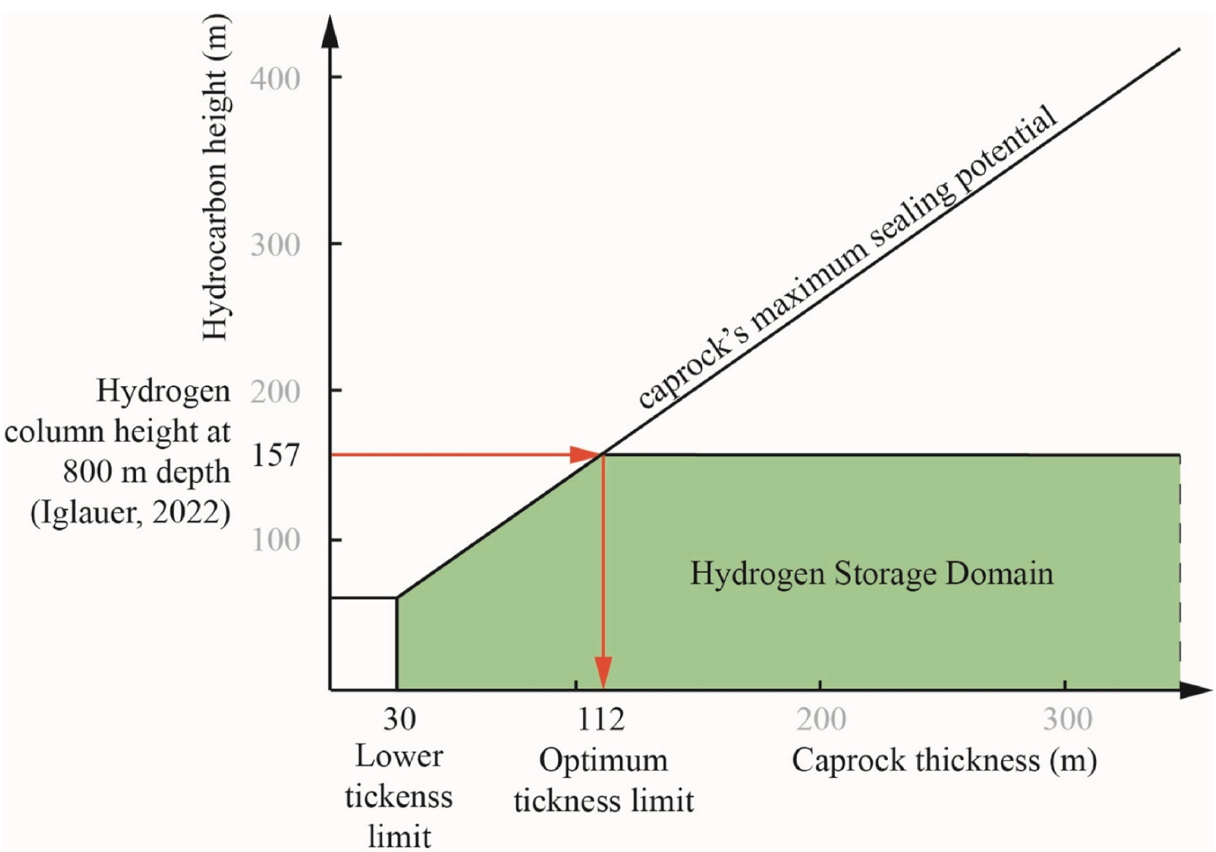

Fig. 4. Plot showing the feasible hydrogen storage domain as a function of hydrogen column height and caprock thickness, where the green area is the domain where exist the underground hydrogen storage and the red arrows indicates the hydrogen column height of 157 m and the correlated optimum caprock thickness (modified from Ref. [96]). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

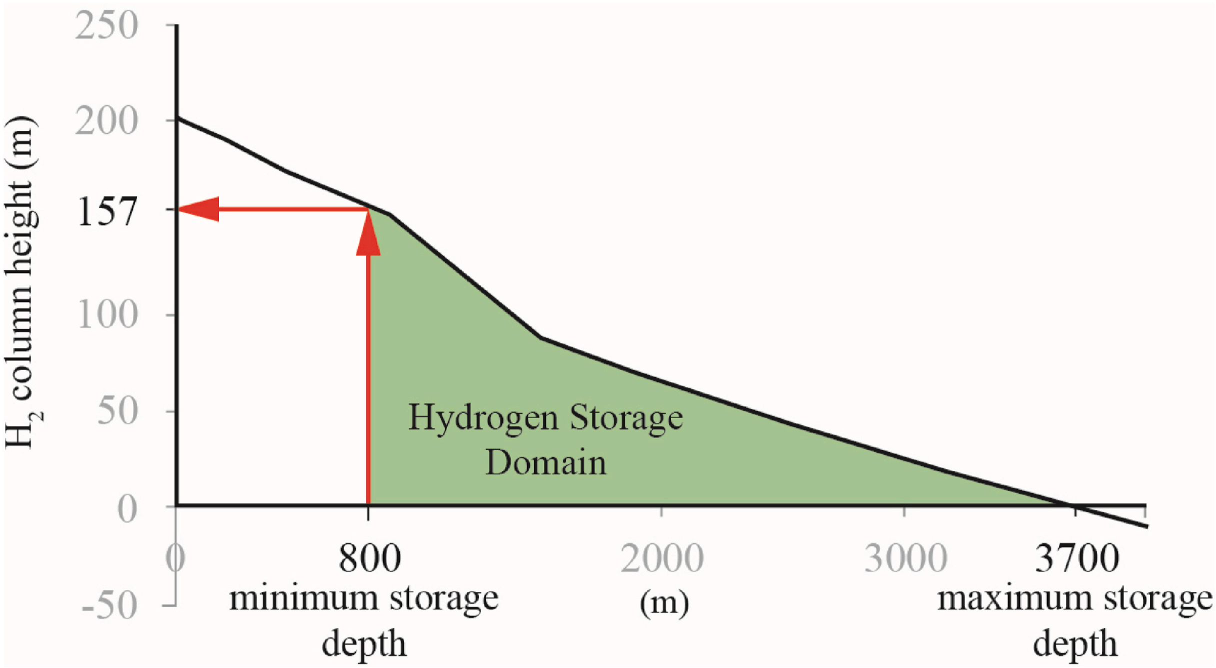

Fig. 5. Plot showing the correlation between hydrogen column height and depth, where the green area is the domain where exist the underground hydrogen storage and the red arrows indicates the minimum storage depth of 800 m and the correlated hydrogen column height (modified from Ref. [97]). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

H_2 RQI $_{Rank}$ values range from 0 (very poor) to 5 (excellent). The threshold values for each parameter have been established based on literature data and are detailed below.

2.1.2.1. Reservoir porosity (ϕ). Porosity is a crucial property of rocks that controls the hydrodynamics of fluid flow in porous formations. In this study, the effective porosity is considered, as it represents the interconnected pore volume available for fluid flow, excluding isolated pores that do not contribute to intrinsic permeability. Low porosity induces higher capillary pressure and a pronounced hysteresis effect in the reservoir, both of which can negatively impact hydrogen storage [31,35,36,38,72]. According to Alms et al. (2023a and references therein), porosity exceeding 20 % is considered good for hydrogen storage, while porosity below 10 % is considered unsuitable for hydrogen storage. Adopting a conservative approach, we selected a minimum porosity of 10 % for our UHS ranking table. Based on Chilingar [103], the optimal porosity value of 28 %, above which a score of 5 is assigned, was chosen as the upper limit. To define the intermediate values between 10 % and 28 %, a linear function was applied.

2.1.2.2. Reservoir permeability (k). To accommodate the demands of frequent injection and withdrawal cycles in hydrogen storage, it is advisable to choose reservoirs characterized by high and uniform intrinsic permeability [29]. Considering these factors, Alms et al. (2023a and references therein) suggest that an intrinsic permeability of 500 mD for the reservoir indicates a favorable geological storage scenario. In contrast, an intrinsic permeability of 100 mD is seen as a cautionary indicator. This study adopts a conservative approach, establishing the minimum intrinsic permeability for UHS at 500 mD, while determining the optimum value to be 4000 mD, based on fine-grained sandstone with a porosity of 28 % from Chilingar [103].

2.1.3. H_2 Site Potential Index

While the previous indices related to Caprock and Reservoir were used to assess the target formation, this new index has been introduced to evaluate the conditions that characterize the reservoir such as salinity, temperature, and depth. Specifically, we have developed the H_2 Site Potential Index (H_2 SPI). These factors are particularly relevant in influencing microbial activity, which can potentially lead to hydrogen losses or contamination through bioreactions [47–49,56].

Understanding the environmental conditions that sustain hydrogen-consuming microbes is essential for ensuring safe and efficient hydrogen storage ([49] and references therein). Thaysen et al. [49] evaluated that temperature (°C) and NaCl concentration (M) are the most critical environmental factors limiting the growth of homoacetogens, methanogens, and sulfate-reducing microorganisms in the subsurface [49]. In contrast, pH does not impose a significant constraint on microbial growth. Most species of microorganisms can tolerate a pH range of two to three units, with optimal growth typically occurring between pH 6 and 7 [49]. Nutrient availability is also not considered a limiting factor, since these microorganisms utilize hydrogen directly as an energy and electron source.

The key parameters identified for the reservoir, which contribute to defining H_2 SPI, are as follows (Table 3):

- Temperature (T)
- Salinity (NaCl)
- Depth (D)

The H_2 SPI is calculated using equation (3):

$$H_2\ SPI = (((T_{Rank} + S_{Rank}) / 2) * D_{Rank}) / 5 \tag{3}$$

H_2 SPI values vary from 0 (very poor) to 5 (excellent). The thresholds for each parameter are derived from hydrogen storage literature [47–49,56] and are outlined below.

2.1.3.1. Temperature (T). We assume a surface temperature of 25 °C and a geothermal gradient of 3 °C for every 100 m [104,105]. Where direct temperature data of the reservoir is unavailable, it has been estimated using this gradient. Several authors agree that temperatures above 40 °C indicate a positive potential for hydrogen storage ([106] and references therein; [48,49,107]) because microbial growth rates are significantly reduced at higher temperatures. To minimize microbial impacts on stored hydrogen, sites with temperatures exceeding 55 °C are preferable, as most microbial strains cannot reproduce above 72 °C [49]. Taking a conservative approach, we selected 55 °C as the minimum acceptable temperature for hydrogen storage, with 72 °C representing the threshold for optimal storage conditions. The temperature range was then divided using a linear function to establish the ranking thresholds.

2.1.3.2. Salinity (NaCl). Salinity, defined as the concentration of dissolved salts in water, is expressed here as moles (M) of NaCl or g/L. The salinity of pore water is crucial for microbial activity, as higher salinity levels can inhibit microbial growth, consequently reducing the risk of hydrogen loss due to biotic reactions [48]. Numerous studies agree that a salinity level exceeding 100 g/L (or 1.7 M NaCl) in formation water is favorable for hydrogen storage [48,49,106,107]. Furthermore, Thaysen et al. [49] suggest that the upper salinity limit for the growth of cultivated strains from all major groups of hydrogen-consuming microorganisms is 3 M NaCl. However, recent studies indicate the potential presence of hydrogen-consuming halophilic microorganisms even at salinities exceeding 3 M NaCl [108–110]. These findings emphasize the need for further research to better understand the role of halophilic microorganisms in subsurface hydrogen storage systems. A conservative approach has been adopted, with salinity values of 1.7 M NaCl and 3 M NaCl chosen as the minimum and optimal thresholds for hydrogen storage, respectively.

2.1.3.3. Depth (D). Similar to the considerations for Carbon Capture, Utilization, and Storage (CCUS), a minimum depth of 800 m is generally recommended for hydrogen storage to prevent contamination of potable waters [106,111–113] (Fig. 5). The optimal depth for underground hydrogen storage (UHS) is directly influenced by the balance between the sealing capacity of the caprock and hydrogen density. Recent studies suggest an optimal depth of 1100 m [65,97,106,107]. However, the maximum storable hydrogen column occurs at a depth of approximately 800 m, and the amount of storable hydrogen gradually decreases with increasing depth, reaching zero at around 3700 m [97] (Fig. 5). Based on these findings, this study sets 800 m as the minimum depth, and 3700 m as the maximum depth for hydrogen storage.

2.1.4. Common parameters for salt caverns

The classification method proposed in this study has been applied to existing hydrogen storage sites worldwide (Fig. 3), including salt caverns and aquifers. An extensive literature review was conducted for each site to gather comprehensive data on their characteristics. However, for salt caverns, certain common features have been assumed due to the limited availability of detailed site-specific information:

- porosity of salt rock as 2.5 % [114].
- porosity of the salt cavern as 100 %
- permeability of the salt cavern as 1×10^9 mD
- Saturated brine salinity

2.2. Underground hydrogen storage suitability index

The Underground Hydrogen Storage Suitability Index (UHS_{SI}) score is the final index comprising the above-described indexes. It is calculated using equation (4), which integrates the CPI $_{Rank}$, RQI $_{Rank}$, and SPI $_{Rank}$, and its values range between 0 (Very Poor) and 5 (Excellent)

$$UHS_{SI} = ((H_2\ CPI_{Rank} + H_2\ RQI_{Rank} + H_2\ SPI_{Rank})\ /\ 3) * ((H_2\ CPI_{Rank} * H_2\ RQI_{Rank} * H_2\ SPI_{Rank})\ /\ (H_2\ CPI_{Rank} * H_2\ RQI_{Rank} * H_2\ SPI_{Rank})) \quad (4)$$

A software tool named **UHSSI Calculator** has been developed to automatically compute the UHSSI. The file is available in the supplementary materials of this article.

3. Results

In this Section we test our ranking method. Selected sites are listed in Fig. 3. The following paragraphs analyze each site's characteristics and corresponding ratings in detail (Table 4). These sites were chosen for analysis because of the extensive literature available on them and data regarding reservoir characteristics and fluid composition changes over time.

3.1. Moss Bluff, Texas (USA) (salt cavern)

Since 2007, Praxair has stored 95 % hydrogen in the Moss Bluff salt dome, located northeast of Houston, Texas [115]. The salt cavern has an estimated capacity of approximately 566×10^3 m^3 at depths ranging from 820 to 1400 m, with a mean diameter of about 60 m and a height of 580 m. The operational pressure varies between 55 and 152 bar. The working gas volume is around 43.7×10^6 m^3 of H_2, corresponding to an energy capacity of 146.7 GWh [76]. According to Hoylman [116], a 900 m thick salt rock layer acts as a natural caprock above the cavern. The calculated reservoir temperature is 64 °C.

By applying the methodology described in this study, the H_2 CPI $_{Rank}$ is 3, the H_2 RQI $_{Rank}$ is 5, and the H_2 SPI $_{Rank}$ is 4. As a result, the UHS_{SI} score for the Moss Bluff salt cavern, derived from the combination of these three sub-indices, is 4.

3.2. Spindletop, Texas (USA) (salt cavern)

Air Liquide USA has operated the world's largest hydrogen storage facility since 2017, located in an underground cavern within the Spindletop salt dome in Beaumont, Texas (US) [76]. This salt cavern is at an average depth of 1340 m [115], with a mean diameter of approximately 70 m, a capacity of about 906×10^3 m^3, and a hydrogen capacity of 274 GWh [76]. The calculated average temperature for the reservoir is 69 °C. The data provided about the storage site can be combined using the methodology described in this document, resulting in a H_2 CPI $_{Rank}$ of 2, a H_2 RQI $_{Rank}$ of 5, and a H_2 SPI $_{Rank}$ of 4. Consequently, the UHS_{SI}, according to the three sub-indices, results in a score of 3.6.

3.3. Clemens dome, Texas (USA) (salt cavern)

Since 1983, ConocoPhillips has stored 95 % pure hydrogen in the Clemens salt dome near Lake Jackson, Texas [76]. This salt cavern has a capacity of approximately 580×10^3 m^3 at an average depth of 1000 m. The cavern is cylindrical, with a diameter of 49 m, a height of 300 m, and a working gas volume of 2.56×10^3 t of H_2 [41,76,115]. The calculated mean temperature of the reservoir is 58 °C.

Using the methodology outlined in this study, the H_2 CPI $_{Rank}$ is 2, the H_2 RQI $_{Rank}$ is 5, and the H_2 SPI $_{Rank}$ is 3. Consequently, the UHS_{SI} score for the Clemens dome salt cavern is 3.3.

3.4. Teesside, Yorkshire (UK) (salt caverns)

Sabic Petroleum Company and Imperial Chemical Industries (ICI)

Table 4
Ranked sites for UHS, where H_2 CPI $_{Rank}$ represents the Hydrogen Caprock Potential Index, H_2 RQI $_{Rank}$ is the Hydrogen Reservoir Quality Index, H_2 SPI $_{Rank}$ indicates the Hydrogen Site Potential Index, and the term "Rank" refers to the final score for the index.

Sites	H2 CPI Rank	H2 RQI Rank	H2 SPI Rank	UHSSI
Moss bluff (USA)	3	5	4	4
Spindletop (USA)	2	5	4	3.6
Clemens dome (USA)	2	5	3	3.3
Teesside (UK)	2	5	0	0
Lobodice (CZ)	1	5	0	0
Beynes (FR)	1	5	0	0

have operated three salt caverns since 1972 in bedded salt with a volume of 70 × 10^3 m^3 in Teesside, UK, resulting in a total storage volume of approximately 210,000 m^3. The stored gas consists of 95 % pure hydrogen, with an average cave depth of 365 m, and the working gas volume is 0.83 × 10^3 t H_2 [41,76,115]. The mean temperature for the reservoir is 69 °C. The information provided about the storage site can be combined using the methodology described in this document, with H_2 CPI $_{Rank}$ yielding a result of 2, H_2 RQI $_{Rank}$ yielding a result of 5, and H_2 SPI $_{Rank}$ producing a result of 0. Consequently, the UHS_{SI}, in accordance with the three sub-indices, culminates in a score of 0.

3.5. Lobodice (Czech Republic) (aquifer)

The case of Lobodice is one of the most well-known hydrogen storage sites, where an alteration in the composition of the stored town gas occurred, resulting in a decrease in hydrogen volume and an enrichment of methane [52,56]. During the storage period, the town gas composition exhibited notable losses of H_2 (from 54 % to 37 %) and CO_2 (from 9.0 % to 3.3 %) along with gains of CH_4 (from 22 % to 40 %) and N_2 (from 2.5 % to 8.6 %). The primary cause of the loss can be attributed to the proliferation of methanogenic microorganisms [76]. Hydrogen was stored in an aquifer at an average depth of 450 m with a porosity of 24 % [56,76] at a temperature of 20 °C [48] and a salinity of 0.25 M NaCl [49]. The caprock consisted of Neocene Baden sediment with a thickness of 300 m, formed by clays of various grain sizes in fine-grained formations [56,76]. The information provided on the storage site can be integrated using the methodology described in this document. The H_2 CPI $_{Rank}$ yields a result of 1, the H_2 RQI $_{Rank}$ yields a result of 5, and the H_2 SPI $_{Rank}$ yields a result of 0. Consequently, the UHS_{SI} culminates in a score of 0, in accordance with the three sub-indices.

3.6. Beynes, ile de France (France) (aquifer)

The Beynes site was operated by Gas de France (GDF) from 1956 to 1974 and is the largest underground storage facility developed in France [76]. GDF stored town gas containing 50 % hydrogen in a saline aquifer with a capacity of 385 × 10^6 m^3 [18]. The reservoir lies at an average depth of 366 m and consists of unconsolidated sandstone with a thickness of 10 m [117]. The average porosity is 25 %, and the average intrinsic permeability is 4000 mD [117]. The caprock has an average thickness of 100 m [76]. During operations, changes in the composition of the stored town gas were observed. It is hypothesized that hydrogen consumption, along with the subsequent increase in hydrogen sulfide, results from the abiotic reduction of pyrite, facilitated by the activity of sulfate-reducing bacteria [118]. The reservoir temperature of 25 °C and pressure of 5–10 MPa support this hypothesis [118]. The information provided on the storage site can be combined using the methodology described in this study. The H_2 CPI $_{Rank}$ yields a result of 1, the H_2 RQI $_{Rank}$ yields a result of 5, and the H_2 SPI $_{Rank}$ yields a result of 0. Consequently, the UHS_{SI}, according to the three sub-indices, culminates in a score of 0.

4. Discussion

Three salt caverns in the USA-Moss Bluff, Clemens Dome, and Spindletop-have been identified as highly suitable for UHS. These sites have successfully operated for industrial hydrogen storage. Salt caverns, which are hollow cavities, provide the optimal conditions for injection and withdrawal cycles. The inherent properties of salt, such as low porosity, low permeability, and high salinity, make it an ideal caprock material, effectively inhibiting the proliferation of hydrogen-consuming microorganisms, while ensuring proper sealing.

Despite the excellent characteristics of salt for hydrogen storage and the successful operation of the Teesside salt cavern (UK) for hydrogen storage, this study has evaluated it as unsuitable for UHS due to its shallow depth. At an average depth of 365 m, the risk of contaminating shallow groundwater in the event of a leak is significant. Even reservoirs with excellent characteristics may be unsuitable for storage if they present other critical limitations, such as insufficient depth. The method proposed in this study attempts to account for these additional factors by integrating multiple geological and environmental parameters to provide a more comprehensive assessment.

The Lobodice site in the Czech Republic has historically faced significant challenges in hydrogen storage. Despite its high porosity and intrinsic permeability, microbial activity has led to substantial hydrogen losses [52,56]. The site's temperature of 20 °C and low salinity of 0.25 M NaCl have created favorable conditions for hydrogen-consuming microorganisms, altering the composition of the stored gas. Additionally, its relatively shallow depth of 450 m has further impacted its suitability. The low score assigned to the Lobodice site by the proposed method aligns with these past storage issues, confirming its unsuitability for UHS.

At the Beynes site in France, the environmental conditions, with a temperature of 25 °C and a lack of data on salinity, raise open questions about the potential for an environment favorable to hydrogen-consuming microorganisms, while the storage depth of 366 m poses a risk to the shallow groundwater. Moreover, evidence indicates that a change in the composition of the stored gas occurred during the town gas storage operations [118]. Therefore, considering the cautionary factors represented by temperature, storage depth, and site characteristics, it can be reasonably concluded that the Beynes site is not a suitable location for UHS. This assessment is further confirmed by the proposed method, which has classified the site as unsuitable for underground hydrogen storage.

The evaluation of hydrogen storage sites using the proposed method has provided a structured and objective classification of their suitability for UHS. The methodology, which incorporates key geological, geochemical, and operational factors, has yielded the following insights:

4.1. Highly suitable sites

Moss Bluff (USA), Clemens Dome (USA), and Spindletop (USA) received high scores due to favorable geological conditions, such as high permeability, reliable caprock integrity, and appropriate site conditions. These sites demonstrate optimal conditions for hydrogen injection and withdrawal, ensuring minimal losses and operational efficiency.

4.2. Unsuitable sites

Teesside (UK), Lobodice (Czech Republic), and Beynes (France) were classified as unsuitable for UHS. The main limiting factors include shallow depth and conditions that encourage high microbial activity.

4.3. Scope and limitations

The proposed Underground Hydrogen Storage Suitability Index (UHSSI) is designed for large-scale application to identify potentially suitable formations for hydrogen storage, focusing on both reservoir and caprock characteristics. Its primary strength lies in providing a standardized, uniform, and replicable framework for classifying underground hydrogen storage (UHS) sites, overcoming the methodological fragmentation currently observed in the literature.

The index integrates geological and biological criteria allowing for a comprehensive assessment of site suitability. A key advantage of the UHSSI is its reliance on a small number of input parameters, each associated with well-defined thresholds derived from an extensive literature review and validated with empirical data, which ensures theoretical robustness.

Among its practical benefits are:

- suitability as a fast and cost-effective screening tool in the early stages of site selection, prior to more detailed site-specific investigations.
- applicability to both salt caverns and deep aquifers, thus widening the range of useable storage types,
- intuitive and lightweight UHSSI Calculator software,
- clarity and ease of interpretation of the final score,

Moreover, the UHSSI framework can be seamlessly integrated into Geographic Information Systems (GIS), enabling simultaneous regional-scale assessments and spatial analyses over large areas.

While the UHSSI provides a standardized and practical tool for the preliminary assessment of underground hydrogen storage sites, several limitations should be acknowledged to correctly frame its applicability.

First, the method evaluates only the static conditions of storage and does not consider the dynamic and geomechanical evolution over time. This is particularly relevant for hydrogen, which may be subjected to rapid injection and withdrawal cycles that can induce significant stress on the reservoir and caprock structures.

Additionally, the UHSSI does not include the total storage volume or economic factors, both of which are essential for determining the feasibility and scalability of storage projects. The model also omits key variables such as hydrogen saturation and the use of a cushion gas, despite their potential impact on storage efficiency and performance.

Another critical limitation is the method's sensitivity to data quality: the accuracy of the UHSSI score heavily depends on the availability and reliability of input data. In data-poor regions, this may lead to significant uncertainty in the final assessment.

Moreover, the proposed method relies on three parameters for each component of the index, which represents a substantial simplification of the geological complexity. While this reduction enhances usability and allows for broader applicability, especially in data-sparse contexts, it may compromise the reliability of the results in geologically complex or highly heterogeneous settings. The complexity of subsurface systems cannot be fully captured by such a limited set of indicators. Nevertheless, for large-scale applications and preliminary screening purposes, the index demonstrates a satisfactory level of reliability and can be considered a valid and appropriate tool within its intended scope of use.

Lastly, the UHSSI is not intended to replace detailed site-specific studies. It should be used as a preliminary screening tool to identify potentially suitable sites, and must be complemented by thorough geological, hydrodynamic, and geochemical investigations during later phases of project development.

5. Conclusion

This study presents a standardized methodology for assessing UHS sites based on caprock, reservoir, and site conditions, leading to the creation of an Underground Hydrogen Storage Suitability Index (UHS_{SI}). This index evaluates parameters such as porosity, permeability, lithology, temperature, sainity and depth, and assigns a score to each site. Specifically, the UHS_{SI} is a comprehensive suitability index derived from the integration of three sub-indices: the H_2 CPI (which evaluates and ranks the caprock), H_2 RQI (which evaluates and ranks the reservoir), and H_2 SPI (which evaluates and ranks the site).

The proposed method was validated using data from six worldwide hydrogen storage sites, the results reveal that while some sites are highly suitable for hydrogen storage, others exhibit limitations that compromise their suitability. Suitable sites, such as Moss Bluff, Clemens Dome, and Spindletop in the USA, demonstrated high scores due to their favorable geological and operational conditions. These conditions are characterized by high permeability, which allows for frequent injection and withdrawal cycles, along with the presence of highly reliable caprock seals. In contrast, sites like Teesside (UK), Lobodice (Czech Republic), and Beynes (France) were considered unsuitable, primarily due to their shallow depths and potential microbial activity. The results of this study align with previous historical evidence of hydrogen loss and further validate the importance of a structured methodology for site selection.

Overall, this study has highlighted the importance of comprehensive geological assessments for UHS and that future research on UHS should also consider other key aspects, such as the maximum permissible carbonate content in reservoirs, the impact of iron-bearing minerals, the relationship between caprock thickness and hydrogen column height, the role of extremophilic microorganisms, and the influence of clay in sandstone reservoirs.

The UHS indexing method proposed in this study could be used to identify and select new potential hydrogen storage sites. We acknowledge that the geological factors considered in this study are not the only aspects to be considered and each identified site must also undergo geomechanical analysis before it can be considered safe for prolonged use. Nonetheless, the geological classification method proposed here offers a cost-effective and reliable tool for initial site assessment and should always be utilized as a preliminary step before further evaluations.

CRediT authorship contribution statement

Lorenzo Borghini: Writing – review & editing, Writing – original draft, Software, Methodology. **Amerigo Corradetti:** Writing – review & editing. **Anna Del Ben:** Writing – review & editing. **Marco Franceschi:** Writing – review & editing. **Lorenzo Bonini:** Writing – review & editing, Supervision, Project administration.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2025.150110.

References

[1] Zainal BS, Ker PJ, Mohamed H, Ong HC, Fattah IMR, Rahman S, Nghiem LD, Mahlia TMI. Recent advancement and assessment of green hydrogen production technologies. Renew Sustain Energy Rev 2024;189:113941. https://doi.org/10.1016/j.rser.2023.113941.
[2] Prinzhofer A, Tahara Cissé CS, Diallo AB. Discovery of a large accumulation of natural hydrogen in Bourakebougou (Mali). Int J Hydrogen Energy 2018;43(42): 19315–26. https://doi.org/10.1016/j.ijhydene.2018.08.193.
[3] Smith NJP, Sherherd TJ, Styles MT, Williams GM. Hydrogen exploration: a review of global hydrogen accumulations and implications for prospective areas in NW Europe. Geol Soc London, Petrol Geol Con Series 2005;6(1):349–58. https://doi.org/10.1144/0060349.
[4] Zwaan F, Brune S, Glerum AC, Vasey DA, Naliboff JB, Manatschal G, Gaucher EC. Rift-inversion orogens are potential hot spots for natural H_2 generation. Sci Adv 2025;11(8). https://doi.org/10.1126/sciadv.adr3418.
[5] Godula-Jopek A. Hydrogen production: electrolysis. Wiley-VCH Verlag GmbH & Co. KGaA; 2015. https://doi.org/10.1002/9783527676507.
[6] Ursua A, Gandia LM, Sanchis P. Hydrogen production from water electrolysis: current status and future trends. Proc IEEE 2011;100(2):410–26. https://doi.org/10.1109/JPROC.2011.2156750.
[7] Chi J, Yu H. Water electrolysis based on renewable energy for hydrogen production. Chin J Catal 2018;39(3):390–4. https://doi.org/10.1016/s1872-2067(17)62949-8.
[8] Kumar SS, Lim H. An overview of water electrolysis technologies for green hydrogen production. Energy Rep 2022;8:13793–813. https://doi.org/10.1016/j.egyr.2022.10.127.
[9] Gao F-Y, Yu P-C, Gao M-R. Seawater electrolysis technologies for green hydrogen production: challenges and opportunities. Curr Opin Chem Eng 2022;36:100827. https://doi.org/10.1016/j.coche.2022.100827.
[10] Dawood F, Anda M, Shafiullah GM. Hydrogen production for energy: an overview. Int J Hydrogen Energy 2020;45(7):3847–69. https://doi.org/10.1016/j.ijhydene.2019.12.059.

[11] Ishaq H, Dincer I, Crawford C. A review on hydrogen production and utilization: challenges and opportunities. Int J Hydrogen Energy 2022;47(62). https://doi.org/10.1016/j.ijhydene.2021.11.149.
[12] Osman AI, Mehta N, Elgarahy AM, Hefny M, Al-Hinai A, Al-Muhtaseb AH, Rooney DW. Hydrogen production, storage, utilisation and environmental impacts: a review. Environ Chem Lett 2021;20(1). https://doi.org/10.1007/s10311-021-01322-8.
[13] Miocic J, Heinemann N, Edlmann K, Scafidi J, Molaei F, Alcalde J. Underground hydrogen storage: a review. Geol Soc London, Special Pub 2023;528(1). https://doi.org/10.1144/sp528-2022-88.
[14] Taibi E, Miranda R, Carmo M, Blanco H. Green hydrogen cost reduction. H2knowledgecentre.com; Hydrogen Knowledge Centre; 2020. https://www.h2knowledgecentre.com/content/researchpaper1613.
[15] Clarke DP, Al-Abdeli YM, Kothapalli G. The impact of renewable energy intermittency on the operational characteristics of a stand-alone hydrogen generation system with on-site water production. Int J Hydrogen Energy 2013;38(28):12253–65. https://doi.org/10.1016/j.ijhydene.2013.07.031.
[16] Kojima H, Nagasawa K, Todoroki N, Ito Y, Matsui T, Nakajima R. Influence of renewable energy power fluctuations on water electrolysis for green hydrogen production. Int J Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2022.11.018.
[17] Heinemann N, Alcalde J, Miocic JM, Hangx SJT, Kallmeyer J, Ostertag-Henning C, Hassanpouryouzband A, Thaysen EJM, Strobel G, Schmidt-Hattenberger C, Edlmann K, Wilkinson M, Bentham M, Haszeldine RS, Carbonell R, Rudloff A. Enabling large-scale hydrogen storage in porous media – the scientific challenges. Energy Environ Sci 2021;14(2):853–64. https://doi.org/10.1039/D0EE03536J.
[18] Tarkowski R. Underground hydrogen storage: characteristics and prospects. Renew Sustain Energy Rev 2019;105:86–94. https://doi.org/10.1016/j.rser.2019.01.051.
[19] Zivar D, Kumar S, Foroozesh J. Underground hydrogen storage: a comprehensive review. Int J Hydrogen Energy 2021;46(45). https://doi.org/10.1016/j.ijhydene.2020.08.138.
[20] Abraham KM. Prospects and limits of energy storage in batteries. J Phys Chem Lett 2015;6(5):830–44. https://doi.org/10.1021/jz5026273.
[21] Dehghani-Sanij AR, Tharumalingam E, Dusseault MB, Fraser R. Study of energy storage systems and environmental challenges of batteries. Renew Sustain Energy Rev 2019;104:192–208. https://doi.org/10.1016/j.rser.2019.01.023.
[22] Ghorbani B, Zendehboudi S, Cata Saady N, Dusseault MB. Hydrogen storage in North America: status, prospects, and challenges. J Environ Chem Eng 2023;11(3):109957. https://doi.org/10.1016/j.jece.2023.109957.
[23] Tarkowski R, Uliasz-Misiak B. Towards underground hydrogen storage: a review of barriers. Renew Sustain Energy Rev 2022;162:112451. https://doi.org/10.1016/j.rser.2022.112451.
[24] Edwards PP, Kuznetsov VL, David WIF, Brandon NP. Hydrogen and fuel cells: towards a sustainable energy future. Energy Policy 2008;36(12):4356–62. https://doi.org/10.1016/j.enpol.2008.09.036.
[25] Sorensen B, Spazzafumo G. Hydrogen and fuel cells. In: Elsevier eBooks. Academic Press; 2018. https://doi.org/10.1016/c2015-0-01635-5.
[26] Staffell I, Scamman D, Velazquez Abad A, Balcombe P, Dodds PE, Ekins P, Shah N, Ward KR. The role of hydrogen and fuel cells in the global energy system. Energy Environ Sci 2019;12(2):463–91. https://doi.org/10.1039/c8ee01157e.
[27] Amirthan T, Perera MSA. Underground hydrogen storage in Australia: a review on the feasibility of geological sites. Int J Hydrogen Energy 2023. https://doi.org/10.1016/j.ijhydene.2022.10.218.
[28] Epelle EI, Obande W, Udourioh GA, Afolabi IC, Desongu KS, Orivri U, Gunes B, Okolie JA. Perspectives and prospects of underground hydrogen storage and natural hydrogen. Sustain Energy Fuels 2022;6(14):3324–43. https://doi.org/10.1039/D2SE00618A.
[29] Saeed M, Prashant Jadhawar. Modelling underground hydrogen storage: a state-of-the-art review of fundamental approaches and findings. Gas Sci Eng 2024;121:205196. https://doi.org/10.1016/j.jgsce.2023.205196. 205196.
[30] Al-Yaseri A, Yekeen N, Mahmoud M, Kakati A, Xie Q, Giwelli A. Thermodynamic characterization of H2-brine-shale wettability: implications for hydrogen storage at subsurface. Int J Hydrogen Energy 2022;47(53):22510–21. https://doi.org/10.1016/j.ijhydene.2022.05.086.
[31] Boon M, Hajibeygi H. Experimental characterization of H2/water multiphase flow in heterogeneous sandstone rock at the core scale relevant for underground hydrogen storage (UHS). Sci Rep 2022;12(1). https://doi.org/10.1038/s41598-022-18759-8.
[32] Wu H, Jayne RS, Pollyea RM. A parametric analysis of capillary pressure effects during geologic carbon sequestration in a sandstone reservoir. Greenhouse Gases: Sci Technol 2018;8(6):1039–52. https://doi.org/10.1002/ghg.1815.
[33] Al-Mukainah H, Al-Yaseri A, Yekeen N, Hamad JA, Mahmoud M. Wettability of shale–brine–H2 system and H2-brine interfacial tension for assessment of the sealing capacities of shale formations during underground hydrogen storage. Energy Rep 2022;8:8830–43. https://doi.org/10.1016/j.egyr.2022.07.004.
[34] Luboń K, Tarkowski R. Influence of capillary threshold pressure and injection well location on the dynamic CO2 and H2 storage capacity for the deep geological structure. Int J Hydrogen Energy 2021;46(58):30048–60. https://doi.org/10.1016/j.ijhydene.2021.06.119.
[35] Hashemi L, Blunt M, Hajibeygi H. Pore-scale modelling and sensitivity analyses of hydrogen-brine multiphase flow in geological porous media. Sci Rep 2021;11(1). https://doi.org/10.1038/s41598-021-87490-7.
[36] Nazari F, Nafchi SA, Asbaghi EV, Farajzadeh R, Niasar VJ. Impact of capillary pressure hysteresis and injection-withdrawal schemes on performance of underground hydrogen storage. Int J Hydrogen Energy 2024;50:1263–80. https://doi.org/10.1016/j.ijhydene.2023.09.136.
[37] Zhou Y, Hatzignatiou DG, Helland JO. On the estimation of CO 2 capillary entry pressure: implications on geological CO 2 storage. Int J Greenh Gas Control 2017;63:26–36. https://doi.org/10.1016/j.ijggc.2017.04.013.
[38] Bahrami M, Amiri E, Zivar D, Ayatollahi S, Mahani H. Challenges in the simulation of underground hydrogen storage: a review of relative permeability and hysteresis in hydrogen-water system. J Energy Storage 2023;73:108886. https://doi.org/10.1016/j.est.2023.108886.
[39] Juanes R, Spiteri EJ, Orr FM, Blunt MJ. Impact of relative permeability hysteresis on geological CO2storage. Water Resour Res 2006;42(12). https://doi.org/10.1029/2005wr004806.
[40] Bo Z, Boon M, Hajibeygi H, Hurter S. Impact of experimentally measured relative permeability hysteresis on reservoir-scale performance of underground hydrogen storage (UHS). Int J Hydrogen Energy 2023;48(36):13527–42. https://doi.org/10.1016/j.ijhydene.2022.12.270.
[41] Wang J, Wu R, Wei M, Bai B, Xie J, Li Y. A comprehensive review of site selection, experiment and numerical simulation for underground hydrogen storage. Gas Sci Eng 2023;118:205105. https://doi.org/10.1016/j.jgsce.2023.205105.
[42] Wang J, Feng X, Wanyan Q, Zhao K, Wang Z, Pei G, Xie J, Tian B. Hysteresis effect of three-phase fluids in the high-intensity injection–production process of sandstone underground gas storages. Energy 2022;242:123058. https://doi.org/10.1016/j.energy.2021.123058.
[43] Chen D, Wang L, Versaillot PD, Sun C. Triaxial creep damage characteristics of sandstone under high crustal stress and its constitutive model for engineering application. Deep Undergr Sci Eng 2023;2(3):262–73. https://doi.org/10.1002/dug2.12033.
[44] Cong L, Hu X. Triaxial rheological property of sandstone under low confining pressure. Eng Geol 2017;231:45–55. https://doi.org/10.1016/j.enggeo.2017.10.005.
[45] Serra-Aguila A, Puigoriol-Forcada JM, Reyes G, Menacho J. Viscoelastic models revisited: characteristics and interconversion formulas for generalized Kelvin–Voigt and Maxwell models. Acta Mech Sin 2019;35(6):1191–209. https://doi.org/10.1007/s10409-019-00895-6.
[46] Voltolini M, Ajo-Franklin J. The effect of CO2-induced dissolution on flow properties in Indiana Limestone: an in situ synchrotron X-ray micro-tomography study. Int J Greenh Gas Control 2019;82:38–47. https://doi.org/10.1016/j.ijggc.2018.12.013.
[47] Strobel G, Hagemann B, Lüddeke CT, Ganzer L. Coupled model for microbial growth and phase mass transfer in pressurized batch reactors in the context of underground hydrogen storage. Front Microbiol 2023;14. https://doi.org/10.3389/fmicb.2023.1150102.
[48] Strobel G, Hagemann B, Huppertz TM, Ganzer L. Underground bio-methanation: concept and potential. Renew Sustain Energy Rev 2020;123:109747. https://doi.org/10.1016/j.rser.2020.109747.
[49] Thaysen EM, McMahon S, Strobel GJ, Butler IB, Ngwenya BT, Heinemann N, Wilkinson M, Hassanpouryouzband A, McDermott CI, Edlmann K. Estimating microbial growth and hydrogen consumption in hydrogen storage in porous media. Renew Sustain Energy Rev 2021;151:111481. https://doi.org/10.1016/j.rser.2021.111481.
[50] Al-Yaseri A, Al-Mukainah H, Yekeen N, Al-Qasim A. Experimental investigation of hydrogen-carbonate reactions via computerized tomography: implications for underground hydrogen storage. Int J Hydrogen Energy 2023;48(9):3583–92. https://doi.org/10.1016/j.ijhydene.2022.10.148.
[51] Al-Yaseri A, Hussaini SR, Fatah A, Al-Qasim AS, Patil PD. Computerized tomography analysis of potential geochemical reactions of carbonate rocks during underground hydrogen storage. Fuel 2024;361:130680. https://doi.org/10.1016/j.fuel.2023.130680.
[52] Trémosa J, Jakobsen R, Le Gallo Y. Assessing and modeling hydrogen reactivity in underground hydrogen storage: a review and models simulating the Lobodice town gas storage. Front Energy Res 2023;11. https://doi.org/10.3389/fenrg.2023.1145978.
[53] Zhan S, Zeng L, Al-Yaseri A, Sarmadivaleh M, Xie Q. Geochemical modelling on the role of redox reactions during hydrogen underground storage in porous media. Int J Hydrogen Energy 2024;50:19–35. https://doi.org/10.1016/j.ijhydene.2023.06.153.
[54] Zeng L, Vialle S, Ennis-King J, Esteban L, Sarmadivaleh M, Sarout J, Dautriat J, Giwelli A, Xie Q. Role of geochemical reactions on caprock integrity during underground hydrogen storage. J Energy Storage 2023;65:107414. https://doi.org/10.1016/j.est.2023.107414.
[55] Bo Z, Zeng L, Chen Y, Xie Q. Geochemical reactions-induced hydrogen loss during underground hydrogen storage in sandstone reservoirs. Int J Hydrogen Energy 2021;46(38):19998–20009. https://doi.org/10.1016/j.ijhydene.2021.03.116.
[56] Kopal L, Čížek P, Milička J. Geological model of Lobodice underground gas storage facility based on 3D seismic interpretation. Contrib Geophys Geodes 2016;46(2):125–35. https://doi.org/10.1515/congeo-2016-0009.
[57] Hosseini M, Ali M, Fahimpour J, Keshavarz A, Iglauer S. Assessment of rock-hydrogen and rock-water interfacial tension in shale, evaporite and basaltic rocks. J Nat Gas Sci Eng 2022;106:104743. https://doi.org/10.1016/j.jngse.2022.104743.
[58] Al-Yaseri A, Esteban L, Yekeen N, Giwelli A, Sarout J, Sarmadivaleh M. The effect of clay on initial and residual saturation of hydrogen in clay-rich sandstone formation: implications for underground hydrogen storage. Int J Hydrogen Energy 2023;48(13):5175–85. https://doi.org/10.1016/j.ijhydene.2022.11.059.
[59] Truche L, Berger G, Destrigneville C, Guillaume D, Giffaut E. Kinetics of pyrite to pyrrhotite reduction by hydrogen in calcite buffered solutions between 90 and

180°C: implications for nuclear waste disposal. Geochem Cosmochim Acta 2010;74(10):2894–914. https://doi.org/10.1016/j.gca.2010.02.027.
[60] Hassannayebi N, Azizmohammadi S, De Lucia M, Ott H. Underground hydrogen storage: application of geochemical modelling in a case study in the Molasse Basin, Upper Austria. Environ Earth Sci 2019;78(5). https://doi.org/10.1007/s12665-019-8184-5.
[61] Yekta AE, Pichavant M, Audigane P. Evaluation of geochemical reactivity of hydrogen in sandstone: application to geological storage. Appl Geochem 2018;95:182–94. https://doi.org/10.1016/j.apgeochem.2018.05.021.
[62] Truche L, Jodin-Caumon M-C, Lerouge C, Berger G, Mosser-Ruck R, Giffaut E, Michau N. Sulphide mineral reactions in clay-rich rock induced by high hydrogen pressure. Application to disturbed or natural settings up to 250 °C and 30 bar. Chem Geol 2013;351:217–28. https://doi.org/10.1016/j.chemgeo.2013.05.025.
[63] Yekta AE, Manceau J-C, Gaboreau S, Pichavant M, Audigane P. Determination of hydrogen–water relative permeability and capillary pressure in sandstone: application to underground hydrogen injection in sedimentary formations. Transport Porous Media 2018;122(2):333–56. https://doi.org/10.1007/s11242-018-1004-7.
[64] Murakami Y, Matsuoka S. Effect of hydrogen on fatigue crack growth of metals. Eng Fract Mech 2010;77(11):1926–40. https://doi.org/10.1016/j.engfracmech.2010.04.012.
[65] Safari A, Zeng L, Nguele R, Sugai Y, Sarmadivaleh M. Review on using the depleted gas reservoirs for the underground H2 storage: a case study in Niigata prefecture, Japan. Int J Hydrogen Energy 2023;48(28):10579–602. https://doi.org/10.1016/j.ijhydene.2022.12.108.
[66] Hagemann B, Panfilov M, Ganzer L. Multicomponent gas rising through water with dissolution in stratified porous reservoirs – application to underground storage of H2 and CO2. J Nat Gas Sci Eng 2016;31:198–213. https://doi.org/10.1016/j.jngse.2016.03.019.
[67] Morozova D, Zettlitzer M, Let D, Würdemann H. Monitoring of the microbial community composition in deep subsurface saline aquifers during CO2 storage in Ketzin, Germany. Energy Proc 2011;4:4362–70. https://doi.org/10.1016/j.egypro.2011.02.388.
[68] Zhang T, Amrani A, Ellis GS, Ma Q, Tang Y. Experimental investigation on thermochemical sulfate reduction by H2S initiation. Geochem Cosmochim Acta 2008;72(14):3518–30. https://doi.org/10.1016/j.gca.2008.04.036.
[69] Ebigbo A, Golfier F, Quintard M. A coupled, pore-scale model for methanogenic microbial activity in underground hydrogen storage. Adv Water Resour 2013;61:74–85. https://doi.org/10.1016/j.advwatres.2013.09.004.
[70] Hagemann B, Rasoulzadeh M, Panfilov M, Ganzer L, Reitenbach V. Mathematical modeling of unstable transport in underground hydrogen storage. Environ Earth Sci 2015;73(11):6891–8. https://doi.org/10.1007/s12665-015-4414-7.
[71] Tarkowski R, Uliasz-Misiak B, Tarkowski P. Storage of hydrogen, natural gas, and carbon dioxide – geological and legal conditions. Int J Hydrogen Energy 2021;46(38):20010–22. https://doi.org/10.1016/j.ijhydene.2021.03.131.
[72] Al-Yaseri A, Sakthivel S, Yekeen N, Norrman K, Nzila A. The influence of microbial activities on the capillary pressure during H2 injection: implications for underground H2 storage. Energy Fuels 2024;38(1):499–505. https://doi.org/10.1021/acs.energyfuels.3c03640.
[73] Boon M, Buntic I, Ahmed K, Dopffel N, Peters C, Hajibeygi H. Microbial induced wettability alteration with implications for Underground Hydrogen Storage. Sci Rep 2024;14(1). https://doi.org/10.1038/s41598-024-58951-6.
[74] Raza A, Arif M, Glatz G, Mahmoud M, Al Kobaisi M, Alafnan S, Iglauer S. A holistic overview of underground hydrogen storage: influencing factors, current understanding, and outlook. Fuel 2022;330:125636. https://doi.org/10.1016/j.fuel.2022.125636.
[75] Martens S, Kempka T, Liebscher A, Lüth S, Möller F, Myrttinen A, Norden B, Schmidt-Hattenberger C, Zimmer M, Kühn M. Europe's longest-operating on-shore CO2 storage site at Ketzin, Germany: a progress report after three years of injection. Environ Earth Sci 2012;67(2):323–34. https://doi.org/10.1007/s12665-012-1672-5.
[76] Sambo C, Dudun A, Samuel SA, Esenenjor P, Muhammed NS, Haq B. A review on worldwide underground hydrogen storage operating and potential fields. Int J Hydrogen Energy 2022;47(54):22840–80. https://doi.org/10.1016/j.ijhydene.2022.05.126.
[77] Liebscher A, Wackerl J, Streibel M. Geologic storage of hydrogen - fundamentals, processing, and projects. Hydrogen Sci Eng: Mater Proc Systems Technol 2016;I:629–58. https://doi.org/10.1002/9783527674268.ch26.
[78] Chen Y, Jin X, Zeng L, Zhong Z, Mehana M, Xiao W, Pu W, Regenauer-Lieb K, Xie Q. Role of large-scale underground hydrogen storage and its pathways to achieve net-zero in China. J Energy Storage 2023;72:108448. https://doi.org/10.1016/j.est.2023.108448.
[79] Kumar S, Jufar SR, Kumar S, Foroozesh J, Kumari S, Bera A. Underground hydrogen storage and its roadmap and feasibility in India toward Net-Zero target for global decarbonization, 350; 2023, 128849. https://doi.org/10.1016/j.fuel.2023.128849.
[80] Le Gallo Y. Assessment of hydrogen storage capacity in porous media at the European scale. Int J Hydrogen Energy 2024;58:400–8. https://doi.org/10.1016/j.ijhydene.2024.01.158.
[81] Barison E, Donda F, Merson B, Le Gallo Y, Réveillère A. An insight into underground hydrogen storage in Italy. Sustainability 2023;15(8):6886. https://doi.org/10.3390/su15086886.
[82] Lackey G, Freeman GM, Buscheck TA, Haeri F, White J, Huerta NJ, Goodman A. Characterizing hydrogen storage potential in U.S. Underground gas storage facilities. Geophys Res Lett 2023;50(3). https://doi.org/10.1029/2022gl101420.
[83] Peecock A, Edlmann K, Mouli-Castillo J, Martinez-Felipe A, McKenna R. Mapping hydrogen storage capacities of UK offshore hydrocarbon fields and investigating potential synergies with offshore wind. Geol Soc London, Special Pub 2023;528(1). https://doi.org/10.1144/sp528-2022-40.
[84] Tarkowski R, Lankof L, Luboń K, Michalski J. Hydrogen storage capacity of salt caverns and deep aquifers versus demand for hydrogen storage: a case study of Poland. Appl Energy 2024;355:122268. https://doi.org/10.1016/j.apenergy.2023.122268.
[85] Caglayan DG, Weber N, Heinrichs HU, Linßen J, Robinius M, Kukla PA, Stolten D. Technical potential of salt caverns for hydrogen storage in Europe. Int J Hydrogen Energy 2020;45(11):6793–805. https://doi.org/10.1016/j.ijhydene.2019.12.161.
[86] Harati S, Gomari SR, Ramegowda M, Pak T. Multi-criteria site selection workflow for geological storage of hydrogen in depleted gas fields: a case for the UK. Int J Hydrogen Energy 2024;51:143–57. https://doi.org/10.1016/j.ijhydene.2023.10.345.
[87] Lankof L, Luboń K, Le Gallo Y, Tarkowski R. The ranking of geological structures in deep aquifers of the Polish Lowlands for underground hydrogen storage. Int J Hydrogen Energy 2024;62:1089–102. https://doi.org/10.1016/j.ijhydene.2024.03.106.
[88] Lewandowska-Śmierzchalska J, Tarkowski R, Uliasz-Misiak B. Screening and ranking framework for underground hydrogen storage site selection in Poland. Int J Hydrogen Energy 2018;43(9):4401–14. https://doi.org/10.1016/j.ijhydene.2018.01.089.
[89] Uliasz-Misiak B, Lewandowska-Śmierzchalska J, Matuła R. Selection of underground hydrogen storage risk assessment techniques. Energies 2021;14(23):8049. https://doi.org/10.3390/en14238049.
[90] Ridolfi RM, Azzaro S, Beaubien SE, Da Pra A, Pontiggia M, Bigi S. Development of a site-screening method for hydrogen storage purposes and its application to an industrial dataset of Italian hydrocarbon reservoirs. Int J Hydrogen Energy 2024;85:841–53. https://doi.org/10.1016/j.ijhydene.2024.08.291.
[91] Borello ES, Bocchini S, Chiodoni A, Coti C, Fontana M, Panini F, Peter C, Pirri CF, Tawil M, Mantegazzi A, Marzano F, Pozzovivo V, Verga F, Viberti D. Underground hydrogen storage safety: experimental study of hydrogen diffusion through caprocks. Energies 2024;17(2). https://doi.org/10.3390/en17020394. 394–394.
[92] Ghaedi M, Andersen PØ, Gholami R. Hydrogen diffusion into caprock: a semi-analytical solution and a hydrogen loss criterion. J Energy Storage 2023;64:107134. https://doi.org/10.1016/j.est.2023.107134.
[93] Hemme C, Van Berk W. Hydrogeochemical modeling to identify potential risks of underground hydrogen storage in depleted gas fields. Appl Sci 2018;8(11):2282. https://doi.org/10.3390/app8112282.
[94] Parkhurst DL, Appelo CAJ. Description of input and examples for PHREEQC version 3: a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. U.S. Geol Survey 2013. https://doi.org/10.3133/tm6a43.
[95] Wentworth CK. A scale of grade and class terms for clastic sediments. J Geol 1922;30(5):377–92. https://doi.org/10.1086/622910.
[96] Ma C, Lin C, Dong C, Luan G, Zhang Y, Sun X, Liu X. Quantitative relationship between argillaceous caprock thickness and maximum sealed hydrocarbon column height. Nat Resour Res 2020;29(3):2033–49. https://doi.org/10.1007/s11053-019-09554-w.
[97] Iglauer S. Optimum geological storage depths for structural H2 geo-storage. J Petrol Sci Eng 2022;212:109498. https://doi.org/10.1016/j.petrol.2021.109498.
[98] Fea I, Abioui M, Nabawy BS, Jain S, Bruno DZ, Kassem AA, Benssaou M. Reservoir quality discrimination of the Albian-Cenomanian reservoir sequences in the Ivorian basin: a lithological and petrophysical study. Geomechan Geophysics Geo-Energy Geo-Res 2021;8(1). https://doi.org/10.1007/s40948-021-00297-8.
[99] Nabawy BS, Al-Azazi NASA. Reservoir zonation and discrimination using the routine core analyses data: the Upper Jurassic Sab'atayn sandstones as a case study, Sab'atayn basin, Yemen. Arabian J Geosci 2015;8(8):5511–30. https://doi.org/10.1007/s12517-014-1632-3.
[100] Amaefule JO, Altunbay M, Tiab D, Kersey DG, Keelan DK. Enhanced reservoir description: using core and log data to identify hydraulic (flow) units and predict permeability in uncored intervals/wells. All Days 1993. https://doi.org/10.2118/26436-ms.
[101] Kozeny J. Uber Kapillare Leitung der Wasser in Boden. Royal Acad Sci 1927;136:271–306.
[102] Carman PC. Fluid flow through granular beds. AIChE 1937;15:150–66.
[103] Chilingar GV. Relationship between porosity, permeability, and grain-size distribution of sands and sandstones. Dev Sedimentol 1964;71–75. https://doi.org/10.1016/s0070-4571(08)70469-2.
[104] Barbier E. Geothermal energy technology and current status: an overview. Renew Sustain Energy Rev 2002;6(1–2):3–65. https://doi.org/10.1016/s1364-0321(02)00002-3.
[105] Kolawole F, Evenick JC. Global distribution of geothermal gradients in sedimentary basins. Geosci Front 2023;14(6):101685. https://doi.org/10.1016/j.gsf.2023.101685.
[106] Alms K, Ahrens B, Gräf M, Nehler M. Linking geological and infrastructural requirements for large-scale underground hydrogen storage in Germany. Front Energy Res 2023;11. https://doi.org/10.3389/fenrg.2023.1172003.
[107] Alms K, Berndsen M, Groeneweg A, Graf M, Nehler M, Ahrens B. Underground hydrogen storage in the bunter sandstone formation in the north German basin: capacity assessment and geochemical modeling. Energy Technol 2023. https://doi.org/10.1002/ente.202300847.

[108] Dopffel N, An-Stepec BA, Bombach P, Wagner M, Passaris E. Microbial life in salt caverns and their influence on H2 storage – current knowledge and open questions. Int J Hydrogen Energy 2024;58:1478–85. https://doi.org/10.1016/j.ijhydene.2024.01.334.

[109] Lee CJD, McMullan PE, O'Kane CJ, Stevenson A, Santos IC, Roy C, Ghosh W, Mancinelli RL, Mormile MR, McMullan G, Banciu HL, Fares MA, Benison KC, Oren A, Dyall-Smith ML, Hallsworth JE. NaCl-saturated brines are thermodynamically moderate, rather than extreme, microbial habitats. FEMS (Fed Eur Microbiol Soc) Microbiol Rev 2018;42(5):672–93. https://doi.org/10.1093/femsre/fuy026.

[110] Merino N, Aronson HS, Bojanova DP, Feyhl-Buska J, Wong ML, Zhang S, Giovannelli D. Living at the extremes: extremophiles and the limits of life in a planetary context. Front Microbiol 2019;10. https://doi.org/10.3389/fmicb.2019.00780.

[111] Della Moretta D, Craig J. Carbon capture and storage (CCS). EPJ Web Conf 2022;268:00005. https://doi.org/10.1051/epjconf/202226800005.

[112] Fan J-L, Shen S, Wei S-J, Xu M, Zhang X. Near-term CO2 storage potential for coal-fired power plants in China: a county-level source-sink matching assessment. Appl Energy 2020;279:115878. https://doi.org/10.1016/j.apenergy.2020.115878.

[113] Proietti G, Conti A, Beaubien SE, Bigi S. Screening, classification, capacity estimation and reservoir modelling of potential CO2 geological storage sites in the NW Adriatic Sea, Italy. Int J Greenh Gas Control 2023;126:103882. https://doi.org/10.1016/j.ijggc.2023.103882.

[114] Samperi L, Minelli G, Omosanya KO, Zappone A, Waldmann N, Nazzareni S, Pauselli C, Bianchi F. Estimation of the physical, petrophysical and mineralogical properties of Messinian salt rocks, Sicily: implications for multidisciplinary applications. Mar Petrol Geol 2020;112:104032. https://doi.org/10.1016/j.marpetgeo.2019.104032.

[115] Malachowska A, Łukasik N, Mioduska J, Gębicki J. Hydrogen storage in geological formations—the potential of salt caverns. Energies 2022;15(14):5038. https://doi.org/10.3390/en15145038.

[116] Hoylman HW. Seismograph evidence on depth of salt column, moss bluff dome, Texas. Geophysics 1946;11(2):128–34. https://doi.org/10.1190/1.1437228.

[117] Jahanbakhsh A, Potapov-Crighton AL, Mosallanezhad A, Kaloorazi NT, Maroto-Valer MM. Underground hydrogen storage: a UK perspective. Renew Sustain Energy Rev 2024;189:114001. https://doi.org/10.1016/j.rser.2023.114001.

[118] Hassanpouryouzband A, Adie K, Cowen T, Thaysen EM, Heinemann N, Butler IB, Wilkinson M, Edlmann K. Geological hydrogen storage: geochemical reactivity of hydrogen with sandstone reservoirs. ACS Energy Lett 2022;7(7):2203–10. https://doi.org/10.1021/acsenergylett.2c01024.

[119] Navaid HB, Emadi H, Watson M. A comprehensive literature review on the challenges associated with underground hydrogen storage. Int J Hydrogen Energy 2022. https://doi.org/10.1016/j.ijhydene.2022.11.225.

[120] Nemati B, Mapar M, Davarazar P, Zandi S, Davarazar M, Jahanianfard D, Mohammadi M. A sustainable approach for site selection of underground hydrogen storage facilities using fuzzy-delphi methodology. J Settl Spatial Plan 2019;SI(6):5–16. https://doi.org/10.24193/jsspsi.2020.6.02.

[121] Zgonnik V. The occurrence and geoscience of natural hydrogen: a comprehensive review. Earth Sci Rev 2020;203:103140. https://doi.org/10.1016/j.earscirev.2020.103140.