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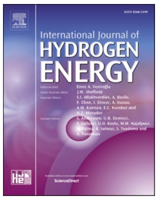

Health, safety and environmental risk assessment tool applied to site selection for geological hydrogen storage in saline aquifers

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ABSTRACT

Hydrogen (H_2) emerges as a pivotal player in the transition to renewable energy sources. To address the seasonal fluctuations in energy dynamics, underground storage emerges as the most efficient approach, and saline aquifers within sedimentary basins as promising repositories for substantial H_2 volumes. However, this potential storage solution remains relatively unexplored. Conducting a comprehensive health, safety, and environment (HSE) risk assessment is vital for the technological advancement and public acceptance of geological H_2 storage sites. This study introduces a methodology designed to select and classify potential formations based on their HSE risks, offering a safety-oriented approach to identifying suitable storage sites. The proposed methodology underwent testing in two deep saline aquifers located in distinct geological contexts within the Iberian Peninsula. The aim of this study is to establish a foundation for further investigations and implementation of geological H_2 storage sites while ensuring safety and adhering to environmental and health standards.

1. Introduction

Climate change and global warming present significant challenges to humanity. In response, most countries are dedicated to promoting environmental sustainability, as outlined in various international agreements. In 2015, 195 countries signed the Paris Agreement, which established goals such as limiting "the increase in the global average temperature below 2 °C above pre-industrial levels," reducing greenhouse gas emissions and primary energy consumption by 55% and 32.5%, respectively, by 2030 compared to 1990, and increasing the share of renewable energy consumption to 32%.

Following the 2021 United Nations Climate Change Conference (COP26), many countries, driven by climate concerns, strengthened their 2030 goals by committing to achieving net-zero emissions by 2070 [1]. Particularly, the European Union (EU) is actively involved in the energy transition to become a climate-neutral continent by the mid-21st century. The EU envisions that 55% of its energy mix will be contributed by renewable sources by 2050, reducing fossil fuel consumption [2,3]. Consequently, the global energy system is transitioning towards renewable energy sources, primarily solar radiation and wind, leading to variations in energy production with atmospheric conditions. Therefore, an energy storage system is essential to balance differences between supply and demand.

Energy can be stored in various forms (electrochemical, mechanical, chemical, electrical, and thermal, among others), and the selected method relies on specific requirements such as amount of energy to be stored, frequency of use and storage, and efficiency, among others [4,5]. Storing unused energy in batteries or capacitors has two main disadvantages, namely their limited lifespan and low capacity [6,7]. To address these issues and enable prolonged energy storage, a plausible approach is to use hydrogen (H_2) [8,9].

H_2 is not considered a primary energy source yet owing to the higher energy input required for its production compared to the energy output [10]. However, H_2 can be efficiently converted into electricity or heat,

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rendering it a valuable energy carrier with capabilities for energy transport and storage [11,12]. H_2, preferably produced from renewable sources, can be stored in geological formations and subsequently pumped to the surface to generate electrical energy during peak demand periods [13–15]. Underground H_2 storage (UHS) is an intriguing alternative, facilitating storage capacities on the order of GWh/TWh for weeks or months [16–18].

Research on UHS in deep geological formations is still in its early stages [19–21]. Various geological structures, such as salt domes, lined and unlined caverns in hard rock, depleted gas and oil fields, and deep saline aquifers, may be used to store H_2 [18,22–28]. Salt domes, in particular, are ideal for storing H_2 gas owing to their highly impermeable salt layer, minimising the probability of leakage [29]. Currently, they are the only tested UHS reservoirs, created through mining procedures to form an underground "storage tank" (Zhang et al., 2022). However, their drawback is limited storage capacity, contingent on the size and number of salt formations with the appropriate thickness and capacity [29,30].

Lined caverns are the newest of the four principal underground storage technologies, and hydrogen has not been stored in them. Because they are costly to develop, rock caverns are likely to be reserved for peaking facilities in regions without other storage options [28].

The thorough research conducted during the hydrocarbon production process highlights the undeniable advantages of utilising depleted gas and oil fields for hydrogen storage [31–33]. Owing to their extensive size, they can accommodate substantial volumes of gas, rendering them highly suitable for large-scale seasonal storage. Additionally, their geological structures contain watertight and well-preserved seal formations, such as structural or stratigraphic traps, which effectively seal the gas. Moreover, these fields are equipped with reusable surface and underground facilities, resulting in saving on implementation costs [22,34].

Prior characterisation studies are necessary for site selection of saline aquifers to ensure structural reliability and integrity of the seal rock [32,35,36]. However, saline aquifers lack existing well infrastructure, necessitating the procurement and installation of all surface and underground components. Thus, the development of saline aquifers is considerably more expensive compared to depleted fields. Despite this disadvantage, saline aquifers possess a high storage capacity and widespread globally positioning them as a viable option with the highest storage capacity [2,37].

The development of a roadmap for large-scale H_2 storage across Europe necessitates the assessment of environmental factors associated with this technology. The EU's transition to a sustainable energy system requires effective management of public health and environmental effects [38,39]. Therefore, conducting a health, safety, and environment (HSE) risk assessment in the initial phase of storage site selection is crucial for estimating critical features, *a priori*, ensuring environmentally safe use and gaining public trust and acceptance of this technology [40]. Moreover, comparing risk levels between available storage sites will facilitate decision-making in their selection.

Currently, there is a lack of a formalised approach for conducting HSE risk assessment in the standardised H_2 storage site selection phase [41]. Similar to CO_2 storage in saline formations, the lack of characterisation data implies a high level of uncertainty during the initial stages [42]. To ensure operational and safety requirements are met, the site selection process must encompass multiple factors associated with gas accumulation under artificial conditions, causing stress imbalances in the geological complex and altering the chemical and flow balance. These changes may give rise to risks such as induced seismicity, fault reactivation, and seal formation failure. In such a scenario, leaked H_2 through the geological medium may reach the atmosphere and/or contaminate groundwater or surface water. Developing an HSE risk assessment methodology for H_2 storage site selection enables the study and assessment of initial information, retrieved from various sources and organised to ensure safety in assessing potential risks resulting from changing natural conditions.

Considering the above, the primary aim of this study was to develop an HSE risk assessment methodology for the initial site selection phase. This methodology was designed to evaluate both site characteristics and information quality, enabling the assessment of site safety and identification of elements contributing most to safety. This, in turn, highlights actions required to reduce uncertainty.

To illustrate its utility, this methodology was applied to two preselected sites on the Iberian Peninsula identified as potential geological H_2 storage sites [43]. These sites are situated in two drainage basins with significantly different characteristics and varying quantities and qualities of available information. The available information is primarily qualitative and is derived from studies and reports on the study areas, sharing a common feature—they were not originally intended to provide safety data. Consequently, the conclusions drawn from the development and application of this methodology will serve as a valuable reference for future research endeavours aimed at enhancing the characterisation of potential H_2 storage sites.

2. Methodology

This methodology was devised for the preliminary assessment of HSE risks associated with geological H_2 storage projects in saline aquifers, considering their geological and geographic context. The methodological design facilitates systematic comparisons between storage sites, adapting to the specific needs of each project.

The conceptual framework of the approach developed in this study incorporates experiences from related technologies, such as CO_2 and natural gas storage, and other uses of the geological environment [44–46]. Additionally, this conceptual framework is based on a model designed to assess HSE risks during the preliminary selection of potential geological CO_2 storage sites [47]. This model underwent modifications to meet specific requirements and adapt to processes associated with H_2 injection, as they may influence the HSE safety of the storage complex. Although the fundamental properties of CO_2 and H_2 storage are similar (including good seal formation and storage rock, among others), the distinct properties of these gases (refer to Table 1) necessitate a specialised study.

The risks related to a H_2 storage project are associated with geomechanical, geochemical, hydrogeological, and microbial processes triggered by H_2 injection [41]. The resultant overpressure on the system displaces fluids from rock pores [48–50] and accumulates H_2 beneath the impermeable seal in the storage formation [51]. The assessment of H_2 storage safety should consider the following aspects.

- The effective functioning of the seal formation is crucial to prevent H_2 leakage from the structure [52]. Characteristics of H_2, such as low viscosity and density and high diffusivity, which are influenced by factors such as brine salinity, pressure, temperature, and the presence of gases, enhance mobility, thereby increasing the risk of H_2 leakage through the seal rock [53–56]. Additionally, the high

Table 1
Comparison of some properties of hydrogen and carbon dioxide (Source: https://encyclopedia.airliquide.com/).

Property	H_2	CO_2
Molecular Weight (g/mol)	2.016	44.01
Critical temperature (°C)	−239.96	31.06
Critical pressure (bar)	13.13	73.83
Critical density (kg/m^3)	31.43	468.19
Triple point temperature (°C)	−259.19	−56.56
Triple point pressure (bar)	0.077	5.187
Gas density (kg/m^3) at 1.013 bar and 25 °C	0.0823	1.8075
Compressibility Factor (Z) at 1.013 bar and 25 °C	1.0006	0.99496
Viscosity (poise) at 1.013 bar and 25 °C	$8.9154 \cdot 10^{-5}$	$1.4932 \cdot 10^{-4}$
Solubility in water (mol/mol) at 1.013 bar and 25 °C	$1.411 \cdot 10^{-5}$	$6.15 \cdot 10^{-4}$

reactivity of H_2 can lead to reactions with the seal rock, potentially dissolving minerals and creating new leakage pathways, posing a risk of containment loss [57]. Several studies, however, indicate that such reactions typically affect only a few meters of the seal rock, without compromising its overall integrity [58]. Nevertheless, this issue should be site-specifically evaluated for its significance. Another critical factor is assessing the capillary sealing efficiency, considering geochemical effects on the hydraulic integrity of the seal rock [59,60].

The integrity of the seal rock is influenced by changes in pore pressure and stress induced by gas injection. A substantial pressure increase during injection reduces the normal stress on the seal rock and potential fault surfaces, leading to mechanical rupture, fracture initiation, and fault reactivation. Additionally, diffusion leaks may arise from deficiencies in the seal rock due to undetected high-permeability zones or discontinuities (fractures and faults) in the seal rock [61,62].

- Injected H_2 influences the chemical equilibrium among dissolved gases, pore water in the reservoir formation, and the rock matrix. Dissolved H_2 reacts with components of pore water, altering the pH of the fluid and triggering mineral dissolution/precipitation reactions. These reactions can create preferential flow pathways associated with changes in rock porosity and permeability, thereby affecting site safety [41]. H_2 may also interact with microorganisms present at the site [63]. However, despite its economic importance due to H_2 consumption [64], this interaction does not pose HSE risks or disrupt the storage system. Consequently, this interaction was not considered in the development of the methodology.
- The pressure within the storage formation must be maintained within an appropriate range to minimise surface subsidence and/or induced seismicity. Insufficient operating pressures may lead to gradual reservoir rock incapacity to support the overlying rock mass, potentially causing compaction. Compaction rates vary across the reservoir due to spatially varying rock properties, resulting in fault formation to accommodate vertical movement from the compaction process. This movement along faults may induce seismicity or rock fracturing if the pressure exceeds the lithostatic pressure.
- Well integrity is crucial for H_2 storage safety, whether designed for H_2 storage or already present on-site. Specifically designed H_2 storage wells require rigorous application of technical and operational procedures to assess their integrity under storage operating conditions. However, evaluating the integrity of existing wells is more challenging due to uncertainties related to the molecular size and diffusion coefficient of H_2. These properties enable H_2 penetration through materials such as steel used in existing wells and distribution systems, potentially affecting their strength [65].

Based on the aspects described above, this methodology indicates the HSE risk level according to the likelihood of H_2 leaks into aquifers or nearby habitats [66] and to information on the characteristics of the reservoir formation and seal and how they may respond to hydrodynamic, geochemical, and geomechanical changes associated with H_2 injection, and on the existence of faults and wells [67], which may compromise the integrity of the reservoir [68], and secondary seals on the storage complex and elements, which may limit the concentration of the gas in elements external to the storage formation.

These data aid in defining key characteristics for site assessment utilising the multi-barrier approach, namely a) primary containment (the site's ability to contain a leak in the reservoir/seal pair), b) secondary containment (the capability to manage a fluid leak in the primary containment), and c) attenuation potential (the likelihood of attenuation once the primary formation leaks and the secondary containment fails) [47]. For assessment purposes, these features are deconstructed into a set of attributes and properties of the storage complex, which will function as proxies for the associated risks. Table 2 provides a detailed overview of these characteristics, attributes, and properties.

Table 2
Features, attributes, and properties.

Features	Attributes	Properties	Proxy for
Primary containment	Primary seals	Thickness	Likely sealing effectiveness
		Lithology	Permeability, porosity
		Demonstrated sealing	Leakage potential
		Depth (distance below ground level)	Density, storage efficiency, capillarity
	Reservoirs	Lithology	Likely storage effectiveness
		Permeability and porosity	Injectivity, capacity
		Thickness	Areal extent of injected plume
		Fracture or primary porosity	Migration potential
		Pressure	Capacity, tendency to fracture
		Hydrology	Transport by groundwater
		Deep wells	Likelihood of well pathways
		Fault permeability	Likelihood of fault pathways
	Regional geology	Trapping mechanism	Integrity and spill point
		Stress state	Induced fracturing, seismicity
		Tectonics	Induced fracturing, seismicity
Secondary containment	Secondary seals	Thickness	Likely sealing effectiveness
		Lithology	Permeability, porosity
		Demonstrated sealing	Leakage potential
Attenuation potential	Surface characteristics	Topography	H_2 plume spreading
		Wind	Plume dispersion
		Climate	Plume dispersion
		Land use	Tendency for exposure
		Population	Tendency for exposure
		Surface water	Form of seepage
	Groundwater hydrology	Regional flow	Dispersion/dissolution
		Pressure	Solubility
		Geochemistry	Solubility
		Salinity	Solubility
	Existing wells	Deep wells	Direct pathway from depth
		Shallow wells	Direct pathway
		Abandoned wells	Direct pathway, poorly known
		Disposal wells	New fluids, disturbance
	Faults	Tectonic faults	Large permeable fault zones
		Normal faults	Seal short-circuiting
		Strike-slip faults	Permeable fault zones
		Fault permeability	Travel time

The primary containment attributes include the primary seal of the formation, the reservoir, and the regional geological conditions. Each attribute is defined by a set of properties that serve as indicators (proxies) for its gas containment capability. Consequently, the reservoir and the primary seal of the formation are characterised by their geological features (lithology, permeability, porosity, thickness, and depth, among others) [21]). The regional geology of the site, reflecting the initial state of the basin, includes the a) trapping mechanism, b) stress state, and c) basin tectonics. Initially, the basin is in equilibrium, but during gas injection and extraction, this equilibrium is disturbed, altering stresses and generating risks of induced seismicity or fault reactivation. Therefore, it is crucial to understand the trapping mechanism, assess whether the initial stresses in the basin are tensile or compressive, and determine the seismicity of the region (low, moderate or high).

Evaluating these structures involves recognising that UHS is a cyclic injection-extraction process designed for H_2 gas to meet energy demand when clean energy falls short [23,69]. Unlike geological CO_2 storage, which experiences compressive stresses, UHS exerts both compressive and tensile stresses cyclically on the ground throughout the project's lifespan, impacting site integrity [70,71]. Identifying existing faults and measuring the initial stress state of the basin are crucial in UHS risk assessment, with induced seismicity considered the most significant event for a potential leak [72].

Cyclic H_2 extraction and injection necessitate further characterisation studies of the terrain under successive stress changes at the site. The continuation of these studies will depend on the type of evaluation conducted in the present study, among other criteria. In this initial phase, the probability of induced seismicity is assessed based on the current stress state of the basin and the existence of faults with dips greater than 60°, as they are more likely to reactivate due to stress changes [69,73,74].

The properties of secondary containment mirror those of the primary containment seal (thickness, lithology, and seal layer tightness), excluding depth. Depth is linked to H_2 storage optimisation; therefore, considering this variable in secondary seals is irrelevant as they only mitigate risks.

Finally, the attenuation potential is influenced by factors such as surface terrain characteristics and groundwater hydrology, serving as retardants or diluents after a leak through the secondary seal. Other considerations for attenuation potential involve identifying direct pathways from the primary or secondary seal to the surface, including wells, interconnected fracturing systems, and faults. The risk magnitude associated with these factors varies based on well and fault types and characteristics [70].

Groundwater acts as a risk reduction attribute by delaying the gas's ability to reach the surface. Subsequent analyses must determine whether these aquifers contain exploitable drinking water to assess the risk of contamination. Surface characteristics, such as topography, climate, wind, land use, and distance to the nearest population, can reduce the time and/or concentration of the contaminant, thereby lowering the risk of exposure for the receptor (environment and society).

For risk assessment, each property is rated for its competence in fulfilling its role (proxy) on a scale from 2 (excellent quality) to -2 (poor quality). The level of certainty is also assessed, ranging from 2 for information from reliable sources directly measuring the property, through 1 for reliable but indirect sources, to 0.1 for highly indirect sources or unreliable information. Available characterisation data (expert knowledge, studies, reports, and publications) serve as a starting point for all assessments, contributing to the aim of assessing the HSE risk level and the corresponding certainty of these estimates. Uncertainty/certainty is maintained as both an input and output value in the methodology, considering the common lack of information in the early stages of a project affecting saline aquifers. In this study, uncertainty is broadly defined, encompassing both true uncertainty and parameter variability.

This methodology allows assigning different weights to each characteristic/attribute/property based on its relative importance for preventing or containing a leak. Expert judgment and related studies on the application of the methodology [45,47,59,75] have been utilised for this purpose (see supplementary information). In H_2 storage, the primary focus is to ensure that H_2 remains in the storage rock for subsequent extraction (linked to economic aspects). Therefore, ensuring the primary containment of H_2 within the geological storage site is of utmost importance because the gas cannot be recovered after a leak from the reservoir rock.

Considering the above, this study developed a simple methodology for comparing, selecting, or rejecting storage sites in the initial stages of project development, taking into account their HSE risks.

3. Application of the methodology

To apply the methodology, two sites deemed *a priori* suitable for UHS, each with significantly different geological contexts, were selected for examination in this study. The first site is situated south of Reus, in the Ebro River basin, whereas the second site is located southwest of Córdoba, in the Guadalquivir River basin. The characteristics of these sites are outlined in the "*Plan de Selección y Caracterización de Áreas y Estructuras Favorables para el Almacenamiento Geológico de* CO_2 *en España"* [Plan for the Selection and Characterisation of Areas and Structures for Favourable Geological Storage of CO_2 in Spain], developed by the Geological and Mining Institute of Spain (*Instituto Geológico y Minero de España*; IGME) and the IRMC in 2009 (https://info.igme.es/algeco2/). The following provides a description of the selected sites.

3.1. Reus site

The Reus site is notable for the high level of available knowledge about this area. Situated 3 km away from Reus, the region is characterised as relatively flat, although it experiences seasonal windiness. Coupled with a semi-humid climate, these conditions pose challenges for the attenuation potential in the event of a leak. Concerning hydrogeology, the site encompasses an aquifer subsystem in Baix Camp, from which water is extracted for irrigation. Consequently, six shallow wells are located near the study area, which also exhibits high nitrate concentrations due to agricultural activity [76].

The study area is situated in the Ebro River basin, a geological and structural component of the foreland basin of the Pyrenees (see Fig. 1). Examining the regional geological context of the Reus site, the northeastern (NE) Iberian Peninsula has witnessed the convergence of the African and European tectonic plates. Tectonic phases in the NE Iberian Peninsula include Hercynian (late Hercynian phase) and Alpine (Pyrenean phase) orogenies, marked by compressive processes, alongside Neogene extensional processes associated with the Gulf of Lion and Valencia Trough margin evolution.

Over an extended period, spanning from the Upper Oligocene to the Aquitanian (Lower Miocene), a system of two fault types emerged: normal (dip-slip) and transfer (strike-slip) faults. NE-SW-trending normal faults led to the formation of several half-grabens or sedimentary sub-basins in the Catalan Coastal Ranges (Empordà, Vallés-Penedés, El Camp, and La Selva half-grabens). NW-SE-trending transfer faults (strike-slip faults), characterised by subvertical faults, caused lateral movement of blocks.

During the Burdigalian (Early Miocene), the tectonic regime shifted from extensional to compressional in the western part of the Western Mediterranean, reactivating previously normal faults with a reverse strike-slip component. Until the Upper Miocene, Miocene basins filled, bounded by normal faults and the Reus and Valls Half-grabens. The Reus site is situated in this area.

The transition between the Gulf of Lion structures and the continental margin features a NW-SE-trending Plio-Quaternary fault system known as the Transfer Zone. The Valls–Reus Depression or Valls–Reus Half-graben is a 60 km-long and 15 km-wide graben, generally tilted by numerous NW-dipping normal faults. Reactivated during the Tertiary and possibly the post-Miocene era as strike-slip faults with substantial horizontal translations.

The most powerful earthquake occurred in March 1927 in Vallès Oriental, registering an epicentral intensity of VII on the Medvedev–-Sponheuer–Karnik scale. Presently, the stress state in the region is

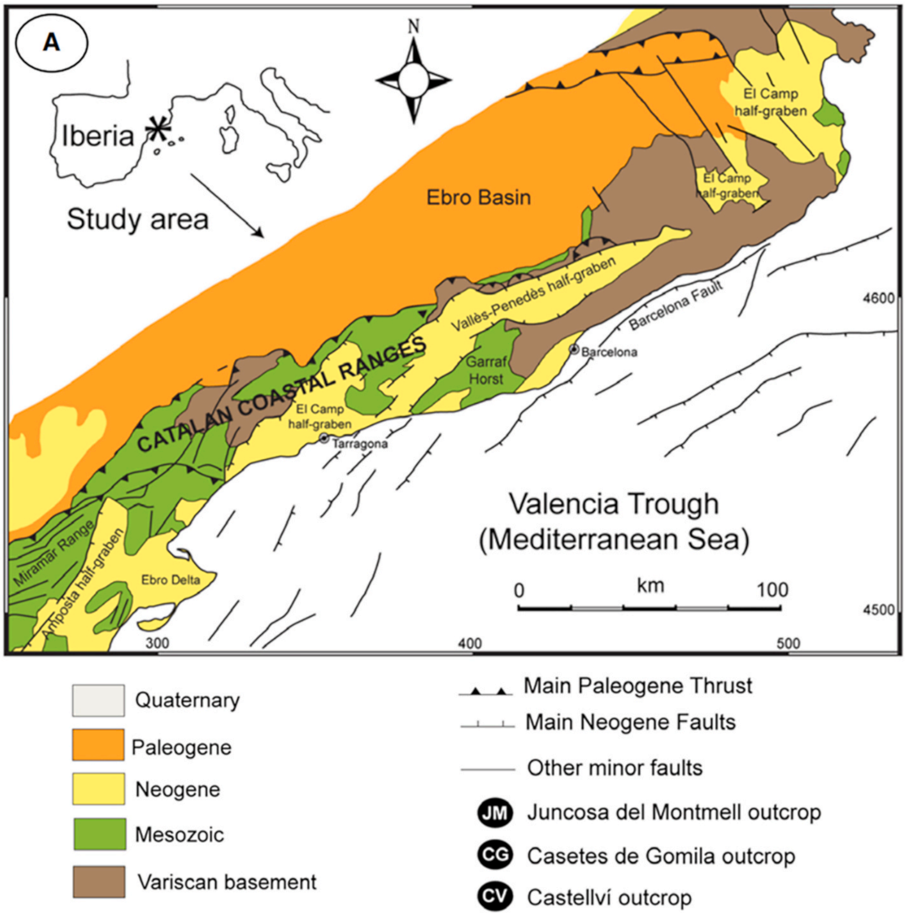

Fig. 1. Geological Map of the Catalan Coastal Ranges. The Reus site is situated in the El Camp graben, west of Tarragona, featuring the emergence of Neogene material [77].

secure, marked by compressive stresses. According to the 2012 seismic hazard map of Spain, published by the National Center for Geographic Information (*Centro Nacional de Información Geográfica* – CNIG) of the Directorate-General of the National Geographic Institute (*Instituto Geográfico Nacional* – IGN), this region experiences medium-low seismicity. For this preliminary study, disregarding induced seismicity, the medium-low seismicity is positive, indicating a lower likelihood of fault reactivation. In summary, this site is considered favourable for H_2 storage but not entirely reliable (Fig. 7).

The Reus site is distinguished by the presence of a seismogenic fault, the El Camp Fault, which, although originally a normal fault, currently functions as a slip fault. This fault is crucial in this study as it spans 40 km with a 60° dip and is currently under review by the National Security Council (Consejo de Seguridad Nacional – CSN) due to its association with Quaternary earthquakes.

Part of the NE-SW-trending fault system, the El Camp Fault initiated its activity as a normal fault in the early Neogene. It can be divided into three sections. The La Selva Sector, currently under CSN review since 2021, exhibits Quaternary activity with an earthquake recurrence interval of approximately 23,000 years. The Vilavella Sector has a slip rate of 0.03 m/ka and a recurrence interval of 17,000 years, whereas the L'Hospitalet Sector has a vertical slip rate of 0.02 m/ka and a recurrence interval of 30,000 years, with the last earthquake occurring 3000 years ago.

These manifestations align with the evolution of the regional stress state, transitioning from extensional stress (forming normal faults) in the Oligocene to the Miocene, to compressive or shear stress (forming strike-slip faults) in the Plio-Quaternary and present day.

Utilising existing boreholes, the main seal, reservoir, and surface layers forming the secondary containment were accurately characterised. The Reus-1 borehole data, directly collected, confirm that the main storage site is an Upper Jurassic carbonate reservoir (see Fig. 2), featuring a 318 m-thick clay stratum (facies Garum) as the seal at a depth of 1432 m. The gross thickness of the storage unit is 144 m, with a net thickness of 66% of the gross thickness, and a culmination depth of 1400 m.

The formation water exhibits a salinity of 31,000 ppm ClNa. Conditions of low salinity and temperature promote microbial proliferation, unsuitable for H_2 storage [79]. The main storage comprises dolomites affected by paleokarstification processes, with 12% porosity and 144 m gross thickness. This high, karstified, and bevelled paleo-relief generates a trap mechanism, creating tight and impermeable conditions [78]. Published by the Geological and Mining Institute of Spain, this information enabled us to assess the primary containment of this storage complex.

The second seal, positioned at a depth of 412 m, is 43 m thick and consists of a layer of calcareous marly sandstones with a high clay content. Despite its depth and thickness, this containment may be deemed reliable for gas containment, although its lithology prevents it from being rated as highly effective. A H_2 storage site ideally features low porosity and permeability, found in halites, shales, and schists, to ensure a high retention capacity for small H_2 molecules [72].

For geological storage, the trapping mechanism is crucial as the primary gas retention mechanism. The high paleo-relief structure of this site creates a trapping mechanism that favours gas retention. During the injection process, the gas displaces the connate fluid to the bottom. Due to its lower density, H_2 diffuses through the storage rock towards the top of the layer, where the seal retains H_2. Simultaneously, this movement of

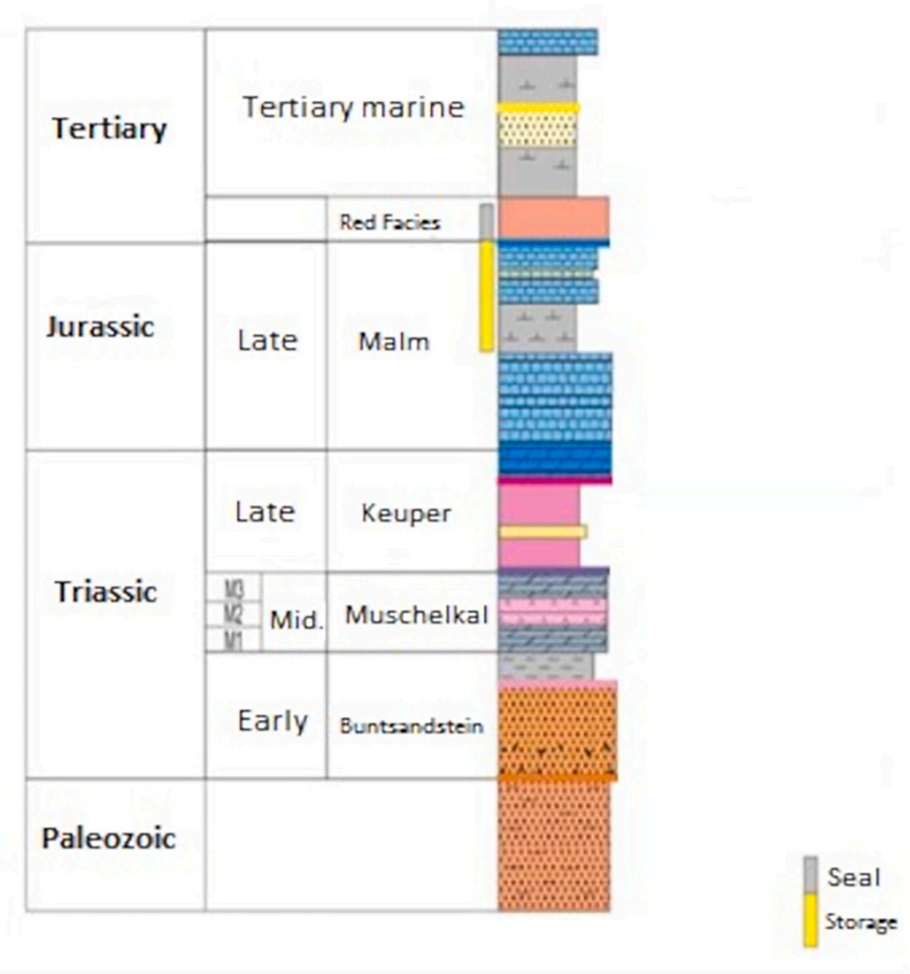

Fig. 2. Stratigraphic column of the Reus-1 borehole, situated in the Ebro basin [78].

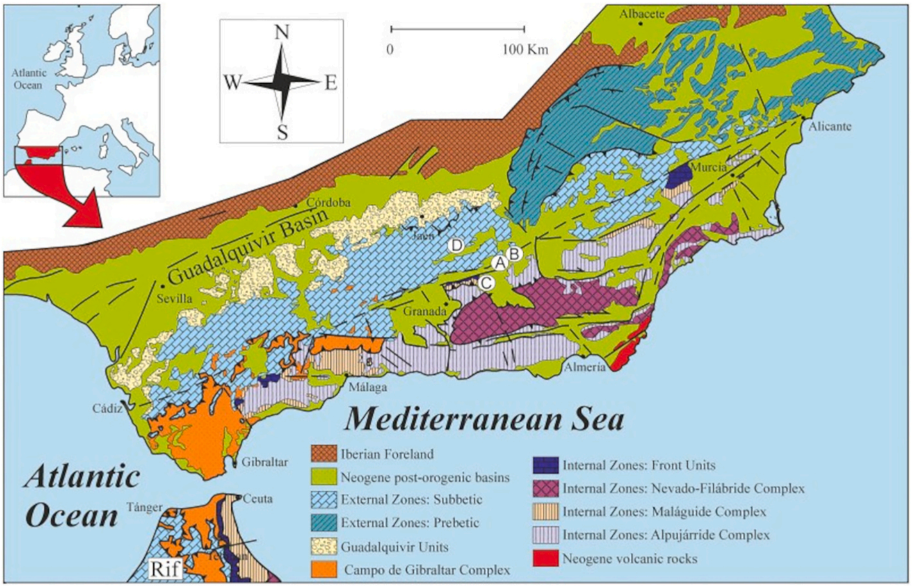

Fig. 3. Geological map of the Guadalquivir Basin. The area of interest exhibits materials from the post-orogenic Neogene [80].

fluids facilitates the spatial distribution of stresses.

3.2. Guadalquivir River site

The Guadalquivir River site is positioned within the Guadalquivir drainage basin, southwest of Córdoba (refer to Fig. 3). The area exhibits a monotonous terrain, encompassing both irrigated and dryland zones. It has an arid climate characterised by minimal wind and low precipitation. The potential injection point, represented by the Guadalquivir River N-1 borehole, is situated 10 km away from the nearest populated area and 12 km from the Guadalquivir River.

Upon analysing the hydrogeological characteristics of the region, a poorly compacted, multilayer aquifer system is identified directly above the storage complex, with no individual aquifer posing significant concern. This aquifer system is surrounded by several free aquifer subsystems, recharged by rainwater, including the aquifer system of the Altiplano de Écija [Écija Plateau]. These aquifer subsystems exhibit salinity levels ranging from 500 to 3000 mg/L and elevated concentrations of chlorides, sodium, nitrates, and magnesium, primarily attributed to agricultural activities [81].

The regional geological context of the Guadalquivir River Basin is characterised as a foreland basin of the Bética Cordillera, comprising a less-known Palaeozoic metamorphic substrate, an early Miocene Base Sands formation, and a Neogene infill divided into four sequences: Bética (Tortonian-Messinian), Andalucía (Messiniense s.s), Marismas (Messinian 2-Pliocene 1), and Odiel (Pliocene 2-Pleistocene) sequences (refer to Fig. 4).

The structural model of the basin is characterised by low-angle monoclines, extensional faults near the passive edge to the NW, and contractional faults in the active edge to the SE. The storage complex comprises traps formed by paleo-reliefs fossilised by the Miocene Base Sands formation. This formation serves as the regional reservoir in the Guadalquivir River Basin, forming a faulted anticlinal trap that dips towards the N. The throw of this trap exceeds 80–100 m, and there is uncertainty regarding the SE extension of its horst closure owing to the limited available seismic data [78].

The Guadalquivir N-1 borehole is situated above a turbiditic channel overlaying the fault trap at the Miocene – Palaeozoic unconformity, marked by a high-angle normal fault.

In contrast to the Reus site, the Guadalquivir River site remains insufficiently characterised. The main seal, located at a depth of 1000 m, is formed by clays and marls (Bética Sequence – Base Sands), whereas the reservoir comprises the Base Sands of the Guadalquivir River basin (Bética Sequence – Guadalquivir Sands) with a thickness of 22 m. The primary trap mechanism of the site corresponds to a trap with a 100 m throw at the Miocene – Palaeozoic unconformity, and this structural confinement is considered highly reliable due to its thickness. For UHS, storage complexes with a relatively thin seal layer pose a higher risk of H_2 leakage; hence, the thickness of the seal should be > 20 m [82,83]. This complex includes 500 m of clay from the Bética Sequence, forming the primary seal.

The Guadalquivir River Basin (or "Surco Bético" [Baetic Basin]) took shape along a large wedge-shaped depression in a SW-NE direction, narrowing from Huelva – Cádiz to Jaén. The southern half of the basin consists of Burdigalian (Lower Miocene) Olistostromes, characterised by chaotically arranged blocks of Mesozoic and Cenozoic materials embedded in a loamy-clayey matrix. The basin commenced filling approximately 19 million years ago (Ma), during the Miocene.

The foreland basin has predominantly remained undeformed despite the compressional and extensional episodes of Alpine tectonics. Its geological evolution has been influenced by the relative movement of the African and Eurasian plates in a north-south direction between the Middle Oligocene and the Late Miocene, followed by an oblique convergence in a west-northwest direction up to the present day.

In the Bética Cordillera, the last significant compressional phase occurred in the Late Middle Miocene, around 12 Ma. Starting from the Tortonian, the penultimate stage of the Miocene, between 11.62 and 7.2 Ma, a widespread extensional regime developed in this area, giving rise to extensive half-grabens due to pre-existing fracturing. Therefore, the neotectonic period in the Bética Cordillera commenced in the Tortonian.

Normal faults in the Palaeozoic basement have affected the tabular cover and the Tertiary fill, although they do not reach the topographic surface, suggesting they may not be currently active. Some interpretations propose that these faults are indeed active but do not penetrate the upper section of the sequence due to deformation accommodating the more plastic Miocene sediments, resulting in blind faults.

From the Lower or Middle Quaternary, a compressional regime with an NNW-SSE direction led to reverse fault movements in inherited systems transverse to the main stress direction, from 1.5 to 1 Ma until the present.

In terms of seismotectonics, the area was influenced by the movement of the African and Eurasian plates between the Middle Oligocene and the Upper Miocene and is currently defined by a state of compressive stress resulting from the collision of the African and European plates [84]. None of the tectonic faults pose a risk of H_2 leakage to the surface. Moreover, no deep boreholes extend beyond the Guadalquivir River N-1 borehole, which was used to characterise the site. On one hand, this lack of boreholes is negative due to the scarcity of direct data to characterise the potential site. On the other hand, it is positive because deep

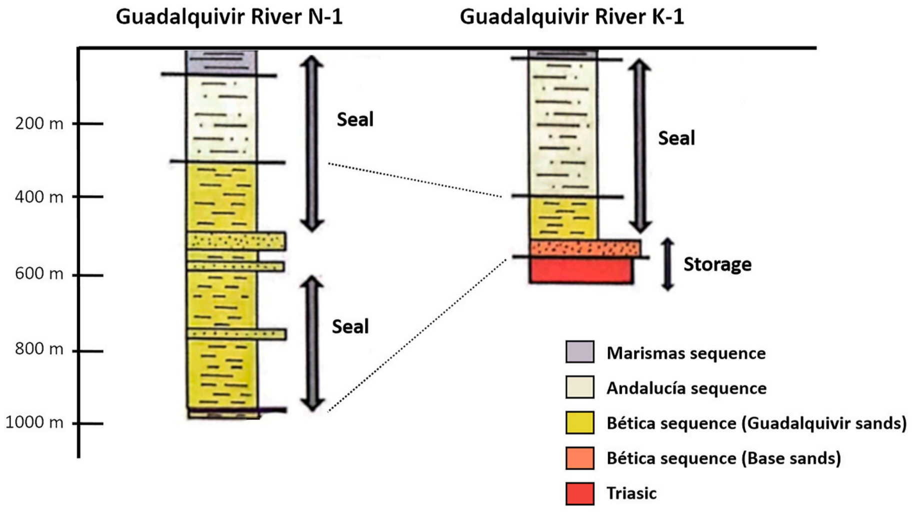

Fig. 4. Regional stratigraphic column of the Guadalquivir River Basin (Adapted from Ref. [78]).

anthropogenic escape routes could compromise the impermeability of this site.

The site was characterised based on the interpretation of seismic lines, analysis of the Río Guadalquivir River N-1 borehole (see Fig. 4), and extrapolations from boreholes around the Guadalquivir. The results indicate that this reservoir rock has approximately 20% porosity, 10^2 mD permeability, and 8000–10,000 ppm connate water salinity. However, the data for the Guadalquivir River site were collected indirectly, introducing a high level of uncertainty associated with its primary containment.

4. Results and discussion

Figs. 5 and 6 illustrate that the selected sites exhibit favourable characteristics concerning safety levels and the certainty associated with the quality of the data.

The data quality of the Reus site aided in performing a preliminary assessment with a high certainty value. Its primary containment is expected to provide highly efficient H_2 retention, contrasting with the secondary containment, primarily due to the lithological and thickness characteristics of the seal formation, receiving a lower score. The attenuation potential is also rated as deficient, considering elements such as the proximity of the city of Reus, regional climate, and hydrology. Additionally, the El Camp fault poses an extra risk, as injection pressure could destabilise the current balance between blocks, prone to slipping due to a dip higher than 60°. On average, the site is favourable, scoring 0.88 on characteristics and 1.83 on certainty (see Fig. 5).

The Guadalquivir storage complex is initially a favourable site for H_2 storage. Its favourable characteristics include both depth and seal thickness of the primary containment, albeit with higher levels of data uncertainty than those of the other two characteristics. Additionally, elements such as the distance to the nearest urban centre and the absence of leakage elements, such as wells and faults, provide the site with good conditions from an attenuation potential standpoint. Conversely, the sealing capacity characteristics of the secondary containment do not favour H_2 storage primarily due to high heterogeneity and poor compaction. On average, the site is favourable, scoring 0.83 on characteristics and 1.50 on certainty (see Fig. 6).

Figs. 7 and 8, plotting the score of each attribute and its certainty, present a more detailed scale of the results mentioned above. The Reus site stands out for the low score of the attribute “Faults,” indicating the presence of faults near the site that may enable non-diffusive H_2 transport to the surface. This low score is influenced by the El Camp fault. In contrast, an attribute that receives a positive rating is “Groundwater Hydrology” because the Baix Camp aquifer subsystem provides the site with a high attenuation potential in the event of a leak. However, these subsystems also pose a risk derived from their shallow water extraction wells, which lowers the favourability score of the site, as illustrated in the radar chart with the attribute “Existing Wells."

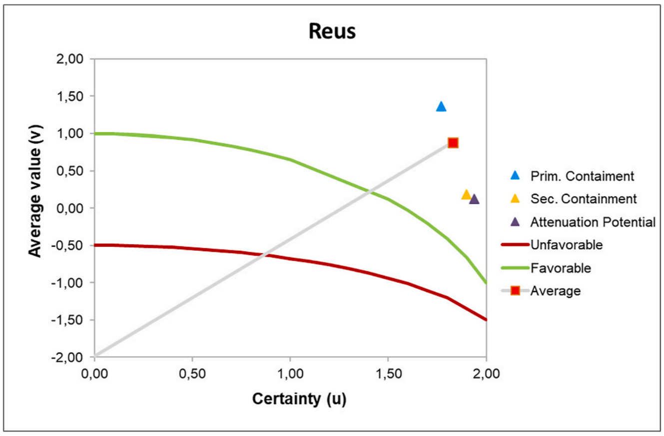

Fig. 5. Graph illustrating the average value as a function of certainty for the Reus site, emphasising its favourable conditions considering data certainty and HSE risks associated with this site.

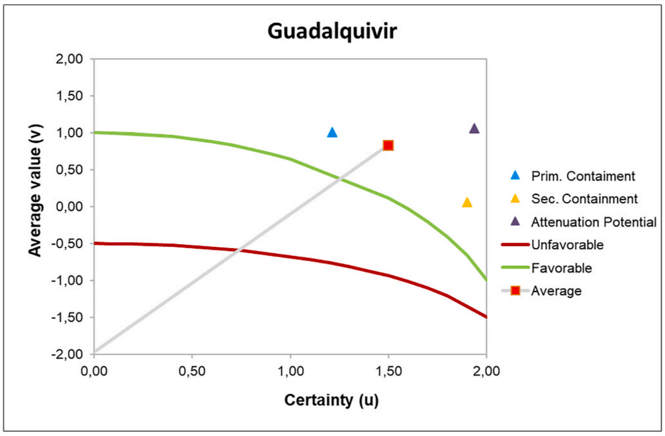

Fig. 6. Graph illustrating the average value as a function of certainty for the Guadalquivir River site, highlighting its favourable conditions considering data certainty and HSE risks associated with this site.

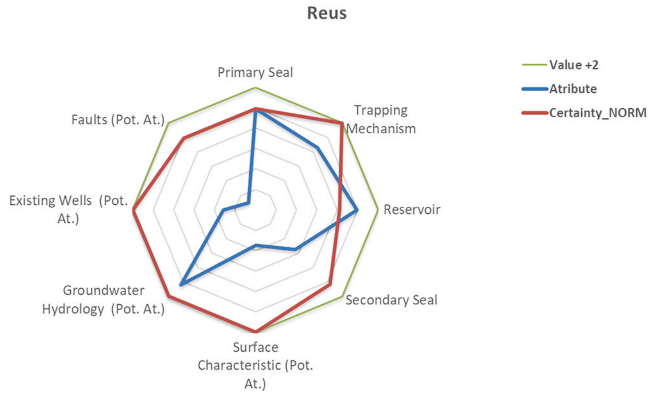

Fig. 7. Radar chart of the Reus site, illustrating the value of each attribute in blue and the certainty in orange. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The high level of knowledge about the location is evident in the certainty of each attribute, as depicted in the radar chart, where all attributes score higher than 1.

As shown in Fig. 8, the Río Guadalquivir River site scores high in favourable characteristics of the attribute “Reservoir,” albeit with high uncertainty due to the lack of direct data, such as data from boreholes reaching the reservoir rock, which raises questions about the reliability of the knowledge. Another attribute that stands out in the radar chart is “Surface Characteristic” because the site is not particularly suitable for coping with a potential H_2 leak due to the local topography and climate.

The attributes with the best scores were “Faults,” thanks to the absence of tectonic faults, followed by the attribute “Groundwater Hydrology” because the multilayer system in the secondary seal layers closest to the surface may facilitate H_2 diffusion and expansion in the event of a leak, thus mitigating the risk of gas accumulation, as observed in the Reus site.

5. Conclusions

HSE risks associated with geological H_2 storage must be estimated to provide decision-makers with necessary and relevant information to

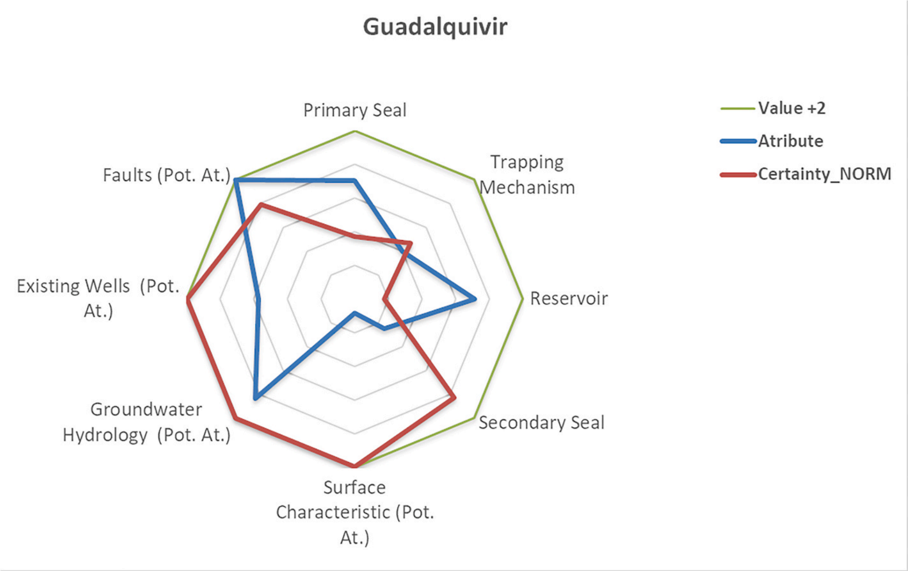

Fig. 8. Radar chart of the Guadalquivir River site, displaying the value of each attribute in blue and the certainty in orange. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

identify deviation controls that may interfere with the aims of such a project and facilitate the communication process with public stakeholders. Even with limited data, our risk assessment and analysis tool can identify, assess, and analyse potential risks associated with operations in geological H_2 storage sites, yielding crucial information for preliminarily selecting saline aquifer sites for such projects. Application of this approach to two potential sites demonstrates that these risks can be analysed considering favourability criteria and the quality of available data, based on their epistemic uncertainty and the natural variability of the elements under study. The transparency and simplicity of this systematic approach enable the evaluator to assign different weights and conduct new tests comparing the effects of these changes on the outcome of the site. In conclusion, despite the complexity of the risks associated with geological H_2 storage, our approach enables us to organise available data to assess safety, empowering decision-makers with useful information for future characterisation studies and for cost-effective resource allocation in implementing risk mitigation measures.

CRediT authorship contribution statement

Antonio Hurtado: Conceptualization, Formal analysis, Supervision, Writing – review & editing. **Alicia López-Mederos:** Data curation, Investigation, Software, Writing – original draft. **Luis F. Mazadiego:** Data curation, Supervision, Writing – review & editing. **Ramón Rodríguez-Pons:** Funding acquisition, Writing – review & editing. **Laura M. Valle-Falcones:** Resources, Software. **Carlos Grima-Olmedo:** Resources, Visualization. **Sonsoles Eguilior:** Conceptualization, Methodology, Validation, Writing – review & editing.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2024.08.180.

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