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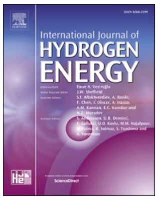

Development of a site-screening method for hydrogen storage purposes and its application to an industrial dataset of Italian hydrocarbon reservoirs

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ABSTRACT

A methodology is presented for the objective and transparent screening of hydrocarbon reservoirs for underground hydrogen storage (UHS), with subsequent testing on a large confidential dataset provided by the energy company Eni. The procedure uses the Analytic Hierarchy Process and the Delphi technique to gather expert opinions and weight 27 screening parameters in terms of: health, safety, and environment; geotechnical performance; and economic performance. A set of scores is produced that characterizes each site in terms of these three categories, as well as a comprehensive site ranking based on their overall suitability for UHS. The results highlight the importance of geotechnical parameters, while the characterization of faults and hydrocarbon type, the onshore or offshore location, the number of wells, and the reservoir architecture yielded the highest individual weights. Potential scores are also estimated for sites with incomplete datasets. Two blind tests evaluated the method's effectiveness against preexisting industrial assessments.

1. Introduction

As nations worldwide strive to meet ambitious climate targets, the role of hydrogen as a versatile energy carrier has gained substantial attention [1], particularly for decarbonizing hard to abate sectors like heavy industry and long-distance transport [2–4]. Thanks to its potential to produce clean energy through a variety of pathways [5–9], including electrolysis powered by renewable sources and steam methane reforming with carbon capture and storage, hydrogen will be an important element in the transition towards a low-carbon economy. The implementation of hydrogen as an energy carrier will require reliable and efficient storage solutions that are capable of satisfying energy demand despite the fluctuation of renewable sources. Underground Hydrogen Storage (UHS) provides a safer and cheaper large-scale solution than using aboveground infrastructure [10]. It involves injecting hydrogen in geological settings such as salt formations, depleted hydrocarbon reservoirs, or saline aquifers, allowing large volumes of gas to be isolated from primary risk factors, such as extreme climate events, oxygen mixing, ignition sources, and vandalism [11–14].

Several review studies compare the different UHS options, providing a detailed overview of their differences, uncertainties, advantages and disadvantages [13–18]. Storing hydrogen in depleted and almost-depleted hydrocarbon reservoirs, the focus of the current research, presents both important advantages and issues to solve. The strengths of this practice are the potential for storage volumes in the terawatt range [19–21] and the suitability for long-term seasonal cycling [11,21–23]. In addition, existing oil and gas infrastructure can be repurposed, thus reducing decommissioning and startup expenses [12,22]. For example, the availability of remnant gas and existing operational data can reduce the expenses for cushion gas supply and reservoir characterization, respectively.

Despite these advantages, various authors [18,24,25] have highlighted issues that might affect storage efficiency due to the physical properties of hydrogen gas and its reactivity with the natural and anthropogenic components of the storage system. Although the tightness of a reservoir system is demonstrated by the trapping of natural gas over geological timescales, the physico-chemical behaviour of hydrogen with caprocks is an area of active research [26–29]. Studies concerning the wettability properties of caprocks found that water is the wetting phase against hydrogen up to a depth of 3700 m, with an apparent reversal of behaviour below this level [29–33]. Hydrogen consumption due to microbial activity could cause the production of hydrogen sulphide, methane, and acids, as well as corrosion, clogging and dissolution phenomena, all of which can reduce the total stored volume. Research examining the influence of reservoir pressure, temperature and salinity

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Abbreviations

AHP	Analytic Hierarchy Process
CCS	Carbon Capture and Storage
Cr	Consistency Ratio
EP	Economic Performance
GP	Geotechnical Performance
HSE	Health, Safety, and Environment
MCDM	Multi-Criteria Decision-Making
NA	North Africa
OGIP	Original Gas In Place
SM	Supplementary Materials
UHS:	Underground Hydrogen Storage

on microbial growth has been used to assess subsurface hydrogen stability, with results showing the need for site-specific characterization due to the high variability of microbial species [34–39]. Physical mechanisms such as viscous fingering, lateral spreading and gravity override are considered manageable by selecting suitable traps and by operating at optimized injection and withdrawal rates [25,40,41], while hydrogen loss due to dissolution in reservoir brines is negligible [42–44]. Regarding reactions with host rocks, carbonates and iron-bearing minerals have been found to be the most reactive while quartz and feldspar minerals the least reactive [42,45–48]. Finally, reactivity with wellbore infrastructure must be understood for both existing and newly constructed wells, with an in-depth evaluation of well conditions for the former and a careful selection of materials for the latter [49,50], given that studies have highlighted negligible [51,52] to relevant [50,53] effects of hydrogen on different types of cement.

Based on the above considerations it is evident that the use of hydrocarbon reservoirs for hydrogen storage is contingent upon a multitude of factors, as partially represented in Fig. 1, thus complicating the selection of suitable storage sites.

The use of Multi-Criteria Decision-Making (MCDM) techniques has become increasingly common to address problems made complex by the presence of a high number of influencing factors [54–56]. MCDMs are a family of techniques based on decomposing problems into their key elements, evaluating these elements, and using formal mathematical procedures to identify one or more preferable alternatives. In particular, the identification of a smaller and more manageable set of alternatives compared to the initial set, which can be subsequently examined for a unique selection, is known as screening [57,58].

This approach has been utilized in many fields, including Carbon

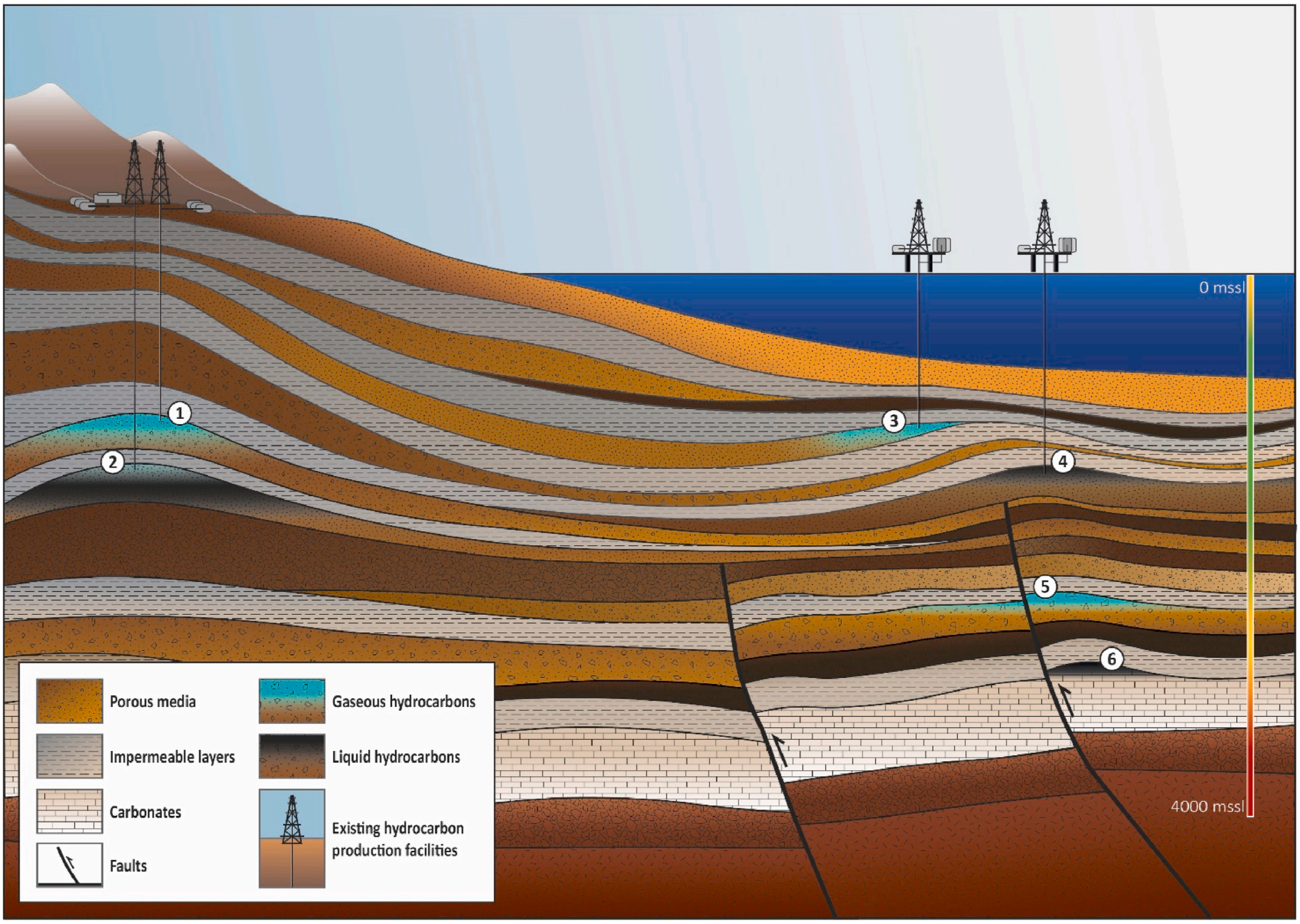


Fig. 1. Schematic illustration of reservoirs with a variable suitability for hydrogen storage in a multi-layered geological setting. The right-side bar represents the positive (green), average (yellow), or negative (red) influence of depth on the storage practice, as assumed in this study. 1) onshore accumulation of gaseous hydrocarbons within an anticlinal trap, crossed by multiple wells; 2) onshore reservoir of oil and natural gas within an anticlinal trap; 3) offshore accumulation of natural gas trapped in a pinch-out structure; 4) offshore oil accumulation within an anticlinal trap with a nearby fault; 5) offshore mild anticline with a gaseous accumulation crossed by a fault; 6) offshore carbonate oil reservoir edged by a fault. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Capture and Storage (CCS) and UHS site selection, to prioritize potential alternatives, speed up the selection procedure, and help make the decision-making procedure more objective and transparent [59].

Bachu [60] proposed an approach for assessing and ranking sedimentary basins suitable for CO_2 storage. This method involved evaluating 15 different criteria, whose records were transformed into normalized values and then aggregated to form a ranking score for each site. In other CCS-related studies, Llamas and Cienfuegos [61] and Llamas and Cámara [62] used the Analytic Hierarchy Process (AHP) approach, an MCDM method designed by Saaty [63,64] to handle both qualitative and quantitative parameters. In the first study, the authors prioritized 23 technical and socio-economic criteria. In the second, they developed the CO_2SiteAssess software, a multi-criteria decision tool that was applied to five Spanish sites described by eleven parameters, again divided in technical and socio-economic groups. Hsu et al. [65] describe the application of the Analytic Network Process (ANP), a generalization of the AHP developed by Saaty [66] to manage problems that cannot be decomposed into a hierarchical structure, to select potential depleted oil and gas reservoirs for CCS by considering eight parameters linked with the sites' capacities.

Fuzzy methods, which are a type of MCDM that are used to cope with vagueness in the decision-making process [59,67], were applied by Deveci and Deveci et al. [68,69] for CCS and UHS purposes, respectively. In the latter case, three different storage scenarios were evaluated using 14 criteria divided into technique characteristics, costs, socio-economic characteristics, and risks. Lewandowska-Śmierzchalska et al. [70] also applied AHP to assess 47 potential UHS candidates in Poland, defining five parameters to describe aquifers and six parameters to describe salt structures, crude oil and natural gas reservoirs. Nemati et al. [71] and Davarazar et al. [72] coupled fuzzy techniques with the Delphi methodology [73] to prioritize various criteria based on expert judgements. In the first case, the authors ranked 18 parameters from technical, economic, health, safety and environment (HSE) and social points of view for a UHS study. In the second case, 19 parameters were considered from the same points of view to define the most important ones in the field of CO_2 storage.

The Delphi method is a systematic process for developing consensus among a panel of experts, particularly useful when empirical evidence is limited or contradictory. The process is mediated by a facilitator and based on different rounds of surveys to assess the importance of various items using a numerical scale. After analysing the first round of responses, a second round focuses on items that did not achieve consensus and allows experts to reconsider their responses based on suggestions from the others. Completion occurs when a satisfying consensus is reached [74–76]. The Delphi method offers a basic structure which can be implemented with various MCDM methods to define the best performing set of options.

Based on this overview, only a small fraction of the site-screening approaches proposed in the literature focus on UHS. Of these, most consider few sites or use generic or a small number of parameters due to the general difficulty in accessing real-world industrial datasets. Additionally, while MCDM methods have proven effective for criteria organization and prioritization, there remains a lack of a comprehensive site-screening workflow that has been rigorously tested on large datasets and that addresses the unique aspects and requirements of hydrogen storage. Addressing these gaps, the present study introduces a site-screening method that integrates both academic knowledge and operational expertise, thereby providing a robust and context-specific approach to UHS site selection. This methodology has the potential to be widely applied in both industrial and research sectors to minimize the times and costs associated with the implementation of hydrogen storage, ensuring a more efficient and informed decision-making process.

This method has been tested on a confidential dataset of 48 candidate sites, each one described using 27 parameters selected from a wider dataset collected during their oil and gas production history. The method is based on the Delphi technique to collect and harmonize the different opinions of the involved participants, while the AHP approach is applied to weight the reciprocal importance of the selected screening parameters. Appropriate normalization techniques are subsequently applied to standardize the various types of dataset records, and calculations are performed to create a final ranking of the sites. The method represents a tool for decision-makers to gather expert opinions that clearly convey the factors influencing their choices, to produce a ranking score for each site, and to outline their suitability in terms of HSE, geotechnical and economic performance.

2. Methods

2.1. Dataset description and selection of the screening parameters

The current methodology was developed using a proprietary dataset that describes 48 depleted and almost-depleted hydrocarbon production sites in Italy. It includes porous and fractured reservoirs characterized by various depths, lithologies and hydrocarbons, though sandstone reservoirs hosting natural gas are the most common. The screening parameters were selected from a wider dataset of 493 parameters (derived from the production history of sites) by considering evidence from the scientific literature and practical insights from industrial collaborators. They comprise 24 site-characterizing attributes plus three additional parameters derived from site-specific data related to the presence of faults and the current productivity status of the sites. Spreadsheets were then used to organize these parameters (Table 1) in a dataset and to perform the screening procedure.

2.2. Weighting of the screening parameters

Parameter weighting quantitatively defines the importance of each parameter against the others, performed by integrating the AHP MCDM. The process involves three main steps: 1) the decomposition of the problem, done by identifying the most important factors involved; 2) the statement of the reciprocal dominance of the elements, performed through a series of comparative judgements on the decomposed elements of the problem; and 3) the use of pairwise comparison matrices to define the relative ratings of the elements [57,77,78]. In the present application, the problem is represented by the screening of various candidate sites for UHS and the decomposed elements are the site-describing parameters selected for the procedure, gathered in groups and supergroups (Fig. 2).

A tree-shaped hierarchic structure is required to produce the pairwise comparisons between the parameters, descending from the main problem down to the lowest levels, which are represented by parameters and groups of parameters. The aspects of health, safety, and environment (HSE), geotechnical performance (GP), and economic performance (EP) were chosen as major screening criteria based on operational and scientific evidence from UHS [71] and CCS [62,79] research, and used as supergroups in the hierarchic model. Except for Decommissioning Status and Porosity Nature parameters, which are used in the final stage to refine the outputs of the method, each parameter was assigned to an HSE, GP, and/or EP supergroup. Note that parameters can be assigned to more than one supergroup because such characteristics may have different (and potentially contrasting) impacts on a site's performance if considered from different points of view. As an example, the number of wells, linked to the possibility of leakage, assumes different weights in HSE (related to risk) and in EP (related to site viability). To quantify the relevance of the individual parameters and their reciprocal dominance in the HSE, GP, and EP branches, a network of surveys and the subsequent calculation procedure were designed in Microsoft Excel. The procedure follows a series of comparative judgements on sets of up to 7 parameters, remaining below the threshold of 10 defined by Saaty [63]. To respect this restriction, the three branches were sub-divided into smaller groups composed of parameters with a comparable impact or area of interest, and a survey was designed for each group.

Table 1
Definitions of parameters, listed in alphabetical order.

Company Participation (%)	Percentage of the site's license owned by Eni.
Datum Depth (mssl)	Depth value measured at datum in meters subsea level, treated as a reference measurement for the depth of the reservoir.
Decommissioning Status	Boolean parameter that describes whether a site is decommissioned or not. Decommissioned sites include flooded or closed sites with permanently sealed wells and out of service infrastructures.
Depletion Status	Boolean parameter that states whether the site is in full production or near shutdown.
Hydrocarbon Drive Mechanisms	Primary and secondary processes that regulated hydrocarbon flow to surface during the site's production history.
Estimated Gas Production (Gm^3)	Predicted or measured total hydrocarbon gas production for productive and closed sites respectively, based on their production history data.
Faulting Description	String parameter about the fault density and positioning in relation to the extent of the hydrocarbon accumulation.
Gas Peak Production (km^3/d)	Maximum daily gas withdrawal measured during the site's production history.
Hydrocarbon Trap Type	String parameter that defines the type of hydrocarbon trap identified during the reservoir exploration phase for oil and gas production.
Hydrocarbon Type	String parameter that describes the hydrocarbon types found in the reservoir.
Initial Pressure at Datum (bar)	Pressure value measured at datum depth in a discovery well, converted from psi unit of measure to bar.
Irreducible SW Mean (%)	Mean of the irreducible water saturation values recorded within a specific reservoir, meaning the lowest water saturation that can be achieved in the reservoir rock by displacing the water with gas.
Mean Net-to-Gross Ratio (%)	Mean value of the net-to-gross ratios measured within the site, expressing the reservoir volume composed of hydrocarbon-bearing rocks.
Mean Porosity (%)	Average value of site's effective porosity measurements.
Number of Wells	Number of wells of any type within the site.
OGIP (Gm^3)	Original Gas in Place, namely a measure of the gas volume stored in the reservoir prior to production.
Onshore/Offshore	Boolean parameter that indicates whether the site is located onshore or offshore.
Permeability Mode (mD)	Most frequently occurring permeability value measured within the reservoir.
Porosity Nature	Boolean parameter that defines whether the site's porosity is primary (typical of porous media reservoirs) or secondary (typical of fractured reservoirs).
Reservoir Architecture	String parameter that pertains to the architectural characteristics of the reservoir.
Reservoir Lithology	String parameter to characterize the reservoir's lithology.
Reservoir Texture	String parameter that describes the average grain size in the reservoir.
Rock Consolidation	Qualitative description of the reservoir rock consolidation status.
Surface Extension (km^2)	Impacted surface-level area enclosing all the boreholes for a specific site. Note that it does not refer to the underground reservoir extension.
Temperature at Datum (°C)	Reservoir temperature measured at datum depth.
Water Production (mbbl)	Reservoir's cumulative water production.
Water Salinity (mol/L)	Salinity of reservoir fluids, converted from grams per liter (g/L) to moles per liter (mol/L) from the original dataset.

The surveys were presented to three experts from Eni and two researchers from La Sapienza University of Rome using a Delphi-method approach to reach a consensual set of judgements [71,72,74–76,80], which are presented in Tables SM-1 to SM-22 in the Supplementary Materials. The central element of the surveys is the pairwise comparison table, which converts verbal judgements into numerical values by using a relative scale that ranges from 1, meaning that the compared parameters have "equal importance", to 9, meaning that one criterion is of "extreme importance" over the other [78]. The resulting values were organized into pairwise comparison matrices (see eq. (1)), in which a set of n parameters ($a_1, a_2, \ldots, a_n$) are compared in correlation matrices according to the weights ($w_1, w_2, \ldots, w_n$) assigned in the survey form [64]:

$$A = \begin{bmatrix} 1 & w_1/w_2 & \ldots & w_1/w_n \\ w_2/w_1 & 1 & \ldots & w_2/w_n \\ \ldots & \ldots & 1 & \ldots \\ w_n/w_1 & w_n/w_2 & \ldots & 1 \end{bmatrix} = \begin{bmatrix} 1 & a_{1,2} & \ldots & a_{1,n} \\ 1/a_{1,2} & 1 & \ldots & a_{2,n} \\ \ldots & \ldots & 1 & \ldots \\ 1/a_{1,n} & 1/a_{2,n} & \ldots & 1 \end{bmatrix} \quad (1)$$

In order to be used for further calculations, these values must be reciprocally consistent and uncontradictory. To assess this, the established methodology involves calculating the Consistency Ratio (C_r) [81–83]; this parameter provides a measure of consistency for the expert judgements by comparing them to a random set of judgements [57,84]. If the C_r falls below the threshold of 0.1, the dominances expressed in the survey are deemed reliable and the weights are acceptable; otherwise, the matrix is considered inconsistent and the judgements within the survey must be revised [63,84]. Once their consistency is verified, the surveys generate weights in percentage for parameters that are specific to the surveyed subgroup (and not to the whole HSE, GP, or EP supergroup). As such, these are local weights ($LW_{jHSE/GP/EP}$) which must be further adjusted to be applicable as global weights ($W_{jHSE/GP/EP}$) in the calculation process. To perform this conversion, the dominance between subgroups within the same supergroup was defined using additional surveys to produce a weight for each one. More specifically, in the HSE supergroup there is only one subgroup (*HSE1*) and thus its weight represents a 100% of its supergroup. In contrast, the GP supergroup consists of 15 parameters divided into three subgroups (*GP1* to *GP3*) while EP consists of 14 divided in two (*EP1* and *EP2*), and thus each individual subgroup represents a fraction of the total supergroup weight ($W_{GP1/GP2/GP3}$ and $W_{EP1/EP2}$, respectively). By applying equations (2)–(4), local weights were multiplied by their respective subgroup weight, resulting in a correspondence between local and global weights for the HSE parameters, and in a weighted conversion for the GP and EP parameters.

$$W_{j_{HSE}} = LW_{j_{HSE}}(W_{HSE1}) \quad (2)$$

$$W_{j_{GP}} = LW_{j_{GP}}(W_{GP1/GP2/GP3}) \quad (3)$$

$$W_{j_{EP}} = LW_{j_{EP}}(W_{EP1/EP2}) \quad (4)$$

where:

$W_{jHSE/GP/EP}$ represents the global weight of the *j*-th parameter in the HSE, GP, or EP supergroup,

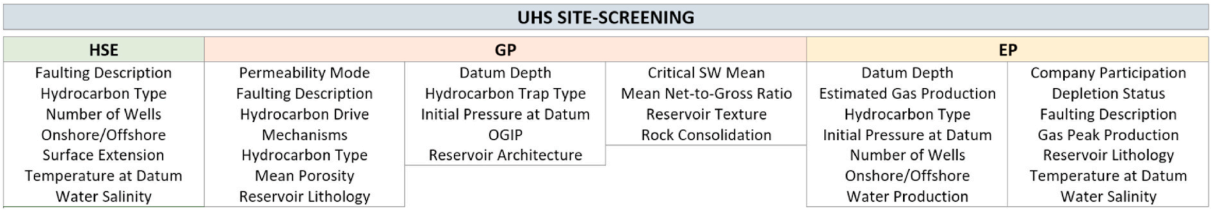
$LW_{jHSE/GP/EP}$ represents the local weight of the *j*-th parameter in the HSE, GP, or EP supergroup, and

$W_{HSE1/GP1/GP2/GP3/EP1/EP2}$ represents the weight of subgroup HSE1, GP1, GP2, GP3, EP1, or EP2.

2.3. Normalization specifics

Reservoirs are complex systems that need a diverse set of parameters to be accurately described. In this regard, the resultant dataset is populated with quantitative attributes in various units of measurement and scales, percentage records, Boolean data, string data, as well as empty records. Normalization was performed to make these parameters mutually comparable, standardizing the records into a common range of values (typically from 0 to 1) for their subsequent use in the calculation process. The process involved applying specific normalization procedures for each different data type, as detailed below, following guidelines from the literature and recommendations from the industry partner.

To normalize the quantitative records, parameters were divided into either "costs", if higher values were considered unfavourable to a better site's performance, or "benefits", if higher values were considered



UHS SITE-SCREENING

HSE	GP			EP	
Faulting Description Hydrocarbon Type Number of Wells Onshore/Offshore Surface Extension Temperature at Datum Water Salinity	Permeability Mode Faulting Description Hydrocarbon Drive Mechanisms Hydrocarbon Type Mean Porosity Reservoir Lithology	Datum Depth Hydrocarbon Trap Type Initial Pressure at Datum OGIP Reservoir Architecture	Critical SW Mean Mean Net-to-Gross Ratio Reservoir Texture Rock Consolidation	Datum Depth Estimated Gas Production Hydrocarbon Type Initial Pressure at Datum Number of Wells Onshore/Offshore Water Production	Company Participation Depletion Status Faulting Description Gas Peak Production Reservoir Lithology Temperature at Datum Water Salinity

Fig. 2. Tree shaped decomposition of the problem. The main problem is the screening of best performing UHS sites, the second level is defined by the major supergroups of health, safety, and environment (HSE), geotechnical performance (GP), and economic performance (EP), and the third level consists of subgroups having no more than seven site-characterizing parameters.

favourable [69,85], followed by the application of Linear Max techniques to proportionally adjust values within the common range [86]. The following summarizes the approach taken for each quantitative attribute. Surface Extension was normalized as a cost parameter to favour sites with a minor impact on the surface environment, while Company Participation was deemed to be a benefit parameter from an economic point of view. Due to pore space reduction caused by high values of water saturation [11], Irreducible SW Mean was normalized as a cost parameter. Estimated Gas Production and Gas Peak Production, treated as an estimate of the reservoir's working gas volume and as a measure of the reservoir's transmissivity potential, respectively, have been normalized as benefit parameters. The pressure parameter, which was represented in the input dataset by Initial Pressure at Datum, influences various storage aspects [16,26,43,87]. In the present setup, it was normalized as a benefit parameter, prioritizing the direct correlation of pressure with the volume of the stored gas, and the effect of high gas pressure in balancing physical phenomena such as viscous fingering and gravity override [11,17,24]. Conceived as a measure of the site's homogeneity, Mean Net-to-Gross Ratio was normalized as a benefit parameter, favouring less heterogenous reservoirs [88]. OGIP was considered as an estimate of the reservoir capacity and thus normalized as a benefit parameter to favour those sites with higher storage volumes. Nevertheless, the optimal dimension of a storage site for UHS is a matter of ongoing debate, as smaller reservoirs are typically perceived as more manageable while larger ones may potentially provide greater storage capacity [16,89,90]; to balance these conflicting opinions, a moderate weight was assigned to this parameter. Finally, owing to the costs related to formation water disposal and the assessment and securing of old wells, Water Production and Number of Wells were normalized as cost parameters.

Some quantitative parameters cause variations in the site's performance as a function of their values falling within specific ranges, such as Datum Depth, Permeability Mode, Mean Porosity, Temperature at Datum, and Water Salinity. To address this, a non-linear normalization was applied by subdividing each parameter into five ranges, based on their individual characteristics, and assigning a discrete weight of 0, 0.25, 0.5, 0.75, or 1.0 (Table 3). For instance, Datum Depth was considered optimal between 500 and 2500 m subsea level (mssl), thus records falling within this range were normalized to 1 and lower coefficients were assigned to depths below 500 mssl or between 2500 and 3500 mssl. According to Iglauer [31], the depth of 3700 mssl must be considered as a threshold for hydrogen storage but given that Datum Depth does not refer to a specific component of the reservoir system, this threshold was moved to a more conservative value of to 3500 mssl and records below this depth were assigned a coefficient of 0. Due to the absence of dataset parameters regarding the microbiological characteristics of reservoirs, Temperature at Datum and Water Salinity parameters were mainly considered for their influence on this aspect [91,92]. Following insights from Thaysen et al. [36] and Nixon et al. [35], two studies that examined the relationship between temperature/salinity conditions and microbial activity in the presence of hydrogen, favourable and unfavourable ranges of values were defined.

To permit the use of qualitative parameters in the calculation procedure, string or Boolean parameter records were assigned numerical values within the normalization range of 0–1. For example, the records of the Depletion Status attribute were normalized to 0 for closed sites, 1 for sites near shutdown and 0.75 for sites in full production. This approach supports sites in which facility conversion could be planned, preventing the invasion of formation water into the gas deposit after production shutdown [13,14]. The attribute Hydrocarbon Drive Mechanisms describes two main processes that can occur during hydrocarbon production: free gas expansion and/or varying levels of water influx. Although free-gas expansion was a drive mechanism during initial reservoir exploitation, it clearly does not play a direct role in hydrogen storage management. However, this parameter does give potentially useful information about reservoir behaviour, and thus, it has been normalized to 1 for UHS due to its positive implications for reservoir pressurization and cushion gas management. Sites with water influx received scores between 0.75 and 0.5 due to the importance of water pressure for withdrawal operations, and a score of 0.25 has been assigned to these records that are less represented among the database, such as "rock compaction", due to their related uncertainties. Faulting Description was normalized taking into account the potential role of structural discontinuities in acting as preferential pathways for the upward migration of deep gases [94], thus lower coefficients were assigned to highly faulted reservoirs (and specifically when faults crossed the hydrocarbon deposits), higher coefficients when faults were absent, and intermediate coefficients when minor faults bordered the reservoir without affecting the hydrocarbon deposits. For Hydrocarbon Type, the presence of residual oil in the reservoir was normalized to 0.25 given the potential for chemical reactions with the stored hydrogen [11,14,15,89], the presence of dry gas was considered optimal and normalized with a value of 1, whereas gas condensate, wet gas, or hydrocarbon mixtures were assigned intermediate values.

Onshore/Offshore is characterized by a contradictory impact on the HSE and EP categories. Offshore sites, due to their isolation, cause a minor perception of risk among communities, who often experience "not in my back yard" (NIMBY) sentiments against the introduction of unconventional practices like UHS [95–98]. At the same time, however, they are more expensive compared to onshore sites. Consequently, offshore sites were normalized as 1 in the HSE and 0.25 in the EP categories, while onshore sites were normalized oppositely.

Reservoir Architecture discriminates between various combinations of compartmentalized, thin-bedded, and multi-layered reservoirs, as well as noting the presence of lateral heterogeneities. In some cases, an indication of potential fault presence is also provided in the record. However, given that faults are better characterized by the Faulting Description parameter, this feature was not considered in the record normalization of this parameter (except for compartmentalized reservoirs). Indeed, compartmentalization is caused by the presence of faults, which divide the hydrocarbon-bearing rock into isolated sectors that are often characterized by different rates of pressure change and enhanced risks of gas leakage and fault reactivation during the storage activities [99,100]. For this reason, these reservoirs were considered less manageable than others and normalized with a low value. Based on the principle that less heterogenous reservoirs are preferred, intermediate values were assigned to thinly bedded reservoirs and higher values to multi-layered reservoirs. However, due to the highly complex nature of the deposits in this dataset, mostly generated by turbiditic currents, no values greater than 0.6 were assigned. Reservoir Lithology was considered from the point of view of its influence on the reservoir reactivity with hydrogen [42,48,101,102] and thus its impact on the maintenance of the stored gas volumes and purity. As such, 0.25 was assigned to carbonate reservoirs, 1 to the less reactive pure sandstones, and intermediate values in the cases of shaly sandstones and silty reservoirs. The Reservoir Texture records range from “very fine” to “coarse”, and the applied normalization favours the coarser-grained reservoirs primarily due to their correlation with other benefit parameters such as porosity and permeability. However, granulometry also impacts the geochemical reactivity of rocks, which is higher for smaller grains due to their larger surface areas [47,103,104].

Rock Consolidation differentiates between “consolidated,” “consolidated-poorly consolidated,” or “poorly consolidated” reservoir media. Due to the superior geomechanical characteristics associated with more consolidated rocks, values of 0.5 were assigned to less consolidated reservoir media, 0.75 to intermediate consolidation, and 1 to fully consolidated reservoir rocks. The Hydrocarbon Trap Type records within the input dataset report various types of anticlinal traps, such as generic, elongated, and four-way dipping anticlines, as well as anticlinal traps with a pinch-out geometry, blocky structures, and combined traps (that incorporate both stratigraphic and structural elements). Similar to Reservoir Architecture records, Hydrocarbon Trap Type records mention potential fault presence. However, for the reasons discussed above, it played a minor role in the normalization of this parameter’s records with the exception of the blocky structures, which are by definition associated with a strong fault presence. A value of 0.25 was assigned to reservoirs divided into blocks, intermediate values were assigned to sites with elongated shapes and faults, and a value of 1 was assigned to combined traps, four-way dipping, and pinched-out anticlines [23,41,105].

After normalization, empty records for any attribute were assigned a value of 0, and thus they do not contribute to the site’s screening score. However, a distinct score estimating the potential of sites with missing data was computed based on the presence of empty records in the dataset (described in detail below).

2.4. Calculation procedure

The ranking score for each site is the result of the aggregation of three scores that describe the sites’ performance from an HSE, geotechnical and economic point of view. The individual scores of these three supergroups ($S_{iHSE/GP/EP}$) were calculated by multiplying the normalized data of each supergroup parameter (n_{ij}) by its assigned weight ($W_{jHSE/GP/EP}$), followed by their summation (eqs. (5)–(7))

$$S_{iHSE} = \sum_{j=1}^{7} n_{ij} \times W_{j_{HSE}} \tag{5}$$

$$S_{iGP} = \sum_{j=1}^{15} n_{ij} \times W_{j_{GP}} \tag{6}$$

$$S_{iEP} = \sum_{j=1}^{14} n_{ij} \times W_{j_{EP}} \tag{7}$$

where:

$S_{iHSE/GP/EP}$ represents the partial score achieved by the i-th site in HSE, GP, or EP ranking, i represents the reservoir site ID (ranging from 1 to 48),

j represents the parameter ID (whose range depends on the parameters in the individual supergroup),

n_{ij} represents the i-th site normalized record belonging to the j-th parameter, and

$W_{jHSE/GP/EP}$ represents the weight of the j-th parameter in the HSE, GP, or EP supergroup.

In the previous equations, empty records were considered as 0 scores. However, given that the dataset consists primarily of sites within a common geological domain, it was considered that missing data could be better approximated with average values rather than 0. Thus, an analogous calculation procedure (detailed in equations (8)–(10)) was performed by replacing the empty records with average values and using them to calculate an additional set of scores. These do not modify the screening scores or site rankings but instead provide additional insight into the potential performance of the sites.

$$P_{iHSE} = \sum_{j=1}^{7} m_{ij} \times W_{j_{HSE}} \tag{8}$$

$$P_{iGP} = \sum_{j=1}^{15} m_{ij} \times W_{j_{GP}} \tag{9}$$

$$P_{iEP} = \sum_{j=1}^{14} m_{ij} \times W_{j_{EP}} \tag{10}$$

where:

$P_{iHSE/GP/EP}$ represents the potential score achieved by the i-th site in the HSE, GP, or EP ranking,

m_{ij} represents the average value that replaces the j-th parameter missing record of the i-th site, and

$W_{jHSE/GP/EP}$ represents the weight of the j-th parameter in the HSE, GP, or EP supergroup.

Calculated using the factorization normalized records (n_{ij}), ranging from 0 to 1, and percentage weights ($W_{jHSE/GP/EP}$), the Si scores can range from 0 to 100 based on the site’s record completeness and quality. They describe site efficiency in terms of HSE, GP, and EP, thus consisting of partial values that must be aggregated to derive a comprehensive site-ranking score (RS_i). Utilizing the AHP once again, supergroup weights of 16.4% (W_{HSE}), 53.9% (W_{GP}), and 29.7% (W_{EP}) were defined. The overall score for each site was then calculated by multiplying the S_i scores by the respective supergroup-assigned weight and summing the values (equation (11)). Similarly, the ranking potential score (RP_i) is obtained by multiplying the P_i scores in HSE, GP, and EP by the supergroup-assigned weight and summing the results (equation (12)).

$$RS_i = S_{iHSE}(W_{HSE}) + S_{iGP}(W_{GP}) + S_{iEP}(W_{EP}) \tag{11}$$

$$RP_i = P_{iHSE}(W_{HSE}) + P_{iGP}(W_{GP}) + P_{iEP}(W_{EP}) \tag{12}$$

RS_i represents the comprehensive ranking score achieved by the i-th site,

S_i represents the partial score achieved by the i-th site in the HSE, GP, or EP ranking,

RP_i represents the ranking potential score achieved by the i-th site in HSE, GP, or EP,

P_i represents the potential score reached by the i-th site in the HSE, GP, or EP ranking, and

$W_{HSE/GP/EP}$ represents the weight of the HSE, GP, and EP supergroups.

2.5. Application of penalties

In accordance with literature findings and operational insights from the industry partner, some reservoir features were considered extremely unfavourable for hydrogen storage either due to feasibility issues or economic constraints. To account for this, two different penalties were applied: a minor penalty was assigned to sites with depth records exceeding 3500 mssl, leading to a 15% reduction of their ranking and potential scores, and a major penalty was applied to decommissioned sites and fractured-media reservoirs, resulting in a 25% reduction of their ranking and potential scores. These penalties are not cumulative, and in case of multiple issues only the higher one is considered.

The depth penalty is due to the previously described change of hydrogen wetting behaviour, which happens below a threshold, as well as economic considerations. Instead, decommissioned sites and fractured media reservoirs were considered as penalizing features for their strongly negative impact on various aspects of the storage practice already assessed through other individual parameters. As an example, closed sites certainly feature wells and other infrastructure that require evaluation, securing, or renewal, and formation water intrusion leads to uncertainties related to fluid displacement during gas injection and water production. Fractured carbonate reservoirs were deemed hazardous if compared to sandstone reservoirs, given the enhanced reactivity of carbonates and the potential of leakage through fracture networks.

3. Results and discussion

An analysis of the most influential parameters derived from the procedure is presented and the primary outcomes of the proposed site-screening approach are subsequently discussed. They comprise three intermediate rankings, categorizing sites based on their efficiency in terms of HSE, geotechnical, and economic performances, as well as a comprehensive site-screening ranking derived through their aggregation.

3.1. Parameters' weights and impacts

During the initial stage of the score calculation process, weights were defined by evaluating the impact of the parameters in terms of HSE, GP, and EP, as listed in Table 2. By applying equation (13), a comprehensive weight for each parameter was further derived in order to determine the influence of the individual parameters in the overall procedure (Tables SM–23).

$$W_j = W_{j_{HSE}}(W_{HSE}) + W_{j_{GP}}(W_{GP}) + W_{j_{EP}}(W_{EP}) \tag{13}$$

Where:

W_j represents the weight of the *j*-th parameter in the overall procedure,

$W_{jHSE/GP/EP}$ represents the weight of the *j*-th parameter in the HSE, GP, and EP rankings, and

$W_{HSE/GP/EP}$ represents the HSE, GP, and EP supergroups weights.

Based on the above, Faulting Description and Hydrocarbon Type were considered pivotal due to their high weights in all the supergroups, with a weight in the overall procedure of 14.9% and 11.2%, respectively, followed by Onshore/Offshore (9.6%) and Number of Wells (7.3%), both having an important role in the HSE and EP supergroups. Reservoir Architecture carried an overall weight of 7.2% for its large impact in the GP supergroup, while both Datum Depth and Initial Pressure at Datum resulted in a weight of 5.8% for their influence in GP and EP. Permeability Mode and Mean Porosity both contributed with a 4.7% weight in the overall procedure, reflecting their importance in GP, as well as Reservoir Lithology that had the same weight due to its impact in both GP and EP. Other parameters had lower weights and played a minor role in the procedure, although the achievement of high scores in a set of minor parameters can have a considerable impact on the overall ranking score of a site.

In total, 27 parameters were involved in the process, a substantial dataset which included numerous features identified as pivotal for UHS based on the scientific literature. Nevertheless, these parameters are derived from the hydrocarbon production history of sites and do not consider some key factors for hydrogen storage that are typically absent from operational data, such as the bio-geochemical reactivity of reservoir units or caprock characteristics. These features may play a central role in a subsequent stage of site characterization, following initial screening to identify the most promising sites. In any case, modifications can easily be made to the screening parameters if these or other suitable data become available for the evaluated sites or if there are changes in stakeholder priorities. Indeed, this method potentially supports the incorporation of an unlimited number of parameters after assigning appropriate weights and normalization criteria, thus enhancing the possibility of customizing it based on specific needs.

In the present configuration, the weights of parameters in the HSE, GP, and EP supergroups were defined based on a joint contribution from university and industry. This was performed by coupling the Delphi technique, used to gather the experts' opinions, and the AHP MCDM process, used to derive weights from pairwise comparisons among the screening parameters. In particular, the AHP survey forms represent a clear tool to visualize the experts' opinions behind the resulting weights, allowing the procedure to present multiple points of view and thus enhance transparency.

For instance, according to equation (13), the weights of the individual supergroups ($W_{HSE/GP/EP}$), namely 16.4% for HSE, 53.9% for GP, and 29.7% for EP, were crucial in calculating the overall weights (W_j). To maintain consistency with prior stages, these weights were determined using an AHP survey form, in which the GP supergroup was valued twice as important as EP and three times more important than HSE as a result of the aggregated academic and industry judgements. To understand this, note that the present method is applied to an industrial dataset deriving from the production history of the sites. Thus, the abundance of technical parameters facilitates an efficiency assessment from a geotechnical point of view and, secondarily, from an economic perspective. Instead, ensuring HSE in the production sites is more closely a function of safety practices and operational procedures that do not figure in such databases. Nevertheless, some geological or technical features might be evaluated based on their indirect or potential impact on the economics and HSE of a site. As an example, the presence of faults and old wells may have an impact on the HSE, whereas the type of hydrocarbon in the reservoir or its depth may influence its economic performance. This aspect was addressed through the possibility of evaluating the same parameter from the points of view of different supergroups. As a result, the GP supergroup is composed of 15 parameters

Table 2

Weights assigned to the parameters through the AHP, listed in alphabetical order. Note that these are percentages, thus summing the weights of the HSE, GP, or EP parameters yields a value of 100.

PARAMETER	HSE	GP	EP	PARAMETER	HSE	GP	EP
Company Participation			2.7	Number of Wells	22.6		12.1
Datum Depth		7.0	6.9	OGIP		3.5	
Depletion Status			1.5	Onshore/Offshore	20.2		21.3
ppppHydrocarbon Drive Mechanisms		5.1		Permeability Mode		8.8	
Estimated Gas Production			4.0	Reservoir Architecture		13.3	
Faulting Description	24.1	15.3	9.2	Reservoir Lithology		4.8	7.1
Gas Peak Production			2.8	Reservoir Texture		1.8	
Hydrocarbon Trap Type		3.7		Rock Consolidation		1.1	
Hydrocarbon Type	9.0	11.6	11.5	Surface Extension	6.6		
Initial Pressure at Datum		7.0	6.9	Temperature at Datum	8.7		5.0
Irreducible SW Mean		3.1		Water Production			4.0
Mean Net-to-Gross Ratio		5.1		Water Salinity	8.7		5.0
Mean Porosity		8.8					

Table 3
Ranges of normalization for Datum Depth, Permeability Mode, Mean Porosity, Temperature at Datum and Water Salinity, assigning scores based on the positive or negative influence determined by a parameter's value falling within a specific range.

Parameter	0	0.25	0.5	0.75	1	References
Datum Depth (mssl)	>3500	3500–3200	3200-2500, <500		500–2500	[31,89]
Permeability Mode (mD)		<10	10–50	50–100	>100	[16,89,93]
Mean Porosity (%)		<10	10–18	18–25	>25	[25,89,93]
Temperature at Datum (°C)		<60	60–80		>80	[35,36]
Water Salinity (mol/L)		<1	1–2	2–4	>4	[36]

and played a primary role in the screening procedure, while the EP and HSE supergroups feature 14 and 7 parameters, respectively, and received lower weights.

3.2. Comparison of HSE, GP, and EP ranks

As an intermediate step of the screening workflow, three scores were calculated for each site reflecting their performance in terms of HSE, GP, and EP, as well as potential scores that estimate these performances in case of missing data in the input dataset. Three rankings were defined according to these scores (Fig. 3, Tables SM–24 in Supplementary Materials), thus providing a preliminary overview of site ranking based on HSE, GP, and EP.

To identify the similarities between the site positions in the three rankings, the Pearson correlation coefficient (r) was chosen. It varies from a maximum value of 1 for a strong direct correlation (i.e., the two rankings are the same) to a minimum value of −1 for a strong inverse correlation (i.e., one ranking is the reverse of the other), whereas a value of 0 represents no correlation. To calculate the correlation coefficient, a pairwise comparison between the rankings was performed, resulting in a 0.72 correlation index between HSE and GP, a −0.08 index between HSE and EP, and a 0.09 index between GP and EP. The positive correlation between HSE and GP indicates that there is a moderate correspondence in the sites' positions in the two rankings. Instead, the very weak correlation between EP and the other rankings suggests that it is independent from them. This behaviour might relate to those parameters in the different supergroups that have the same or contrasting normalization behaviours (i.e., benefit or cost). For example, the reservoir temperature and salinity conditions, which affect microbial activity and thus the occurrence of biological byproducts, were considered as a cost parameter in both HSE and EP. In the former this is because of safety issues related to the potential formation of H_2S, while in the latter it is because of the possibility of metal corrosion and reduced gas purity. In contrast, the offshore location of a site is considered a benefit in HSE, due to isolation from populated areas, and as a cost in EP, due to the higher economic impact of such facilities. Indeed, considering the parameters from different points of view might yield similar ranking results, as happened for HSE and GP, or different results, as for HSE and EP. Moreover, most of the HSE parameters are also considered in the GP supergroup, whereas EP involved specific parameters (like Estimated Gas Production or Company Participation) that results in a minor overlap between the resulting ranks.

An integrated assessment of these parameters improves transparency in decision-making while allowing for the generation of multiple insights from the same input dataset. These insights include the final site ranking as well as intermediate rankings based on HSE, GP, and EP criteria, providing valuable information on the efficiency of sites across various aspects of the storage practice.

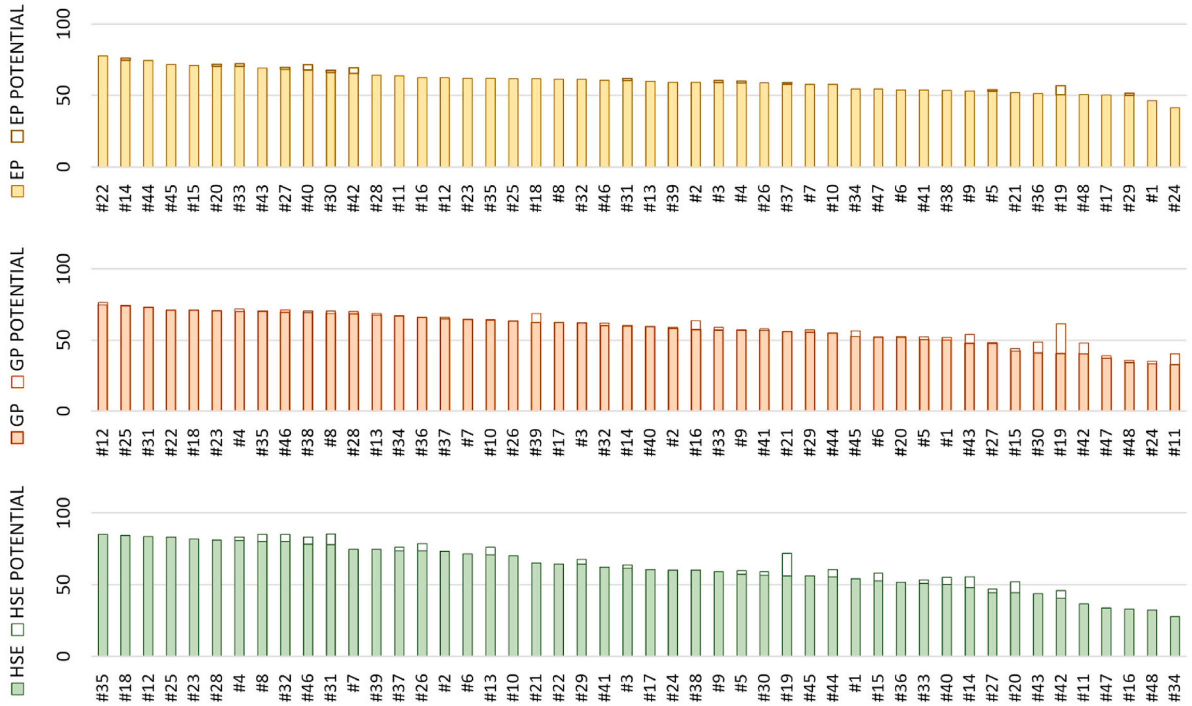


Fig. 3. Bar charts representing three rankings based on the sites' scores achieved in the HSE, GP, and EP supergroups. The horizontal axis lists site IDs ranging from 1 to 48, while the vertical axis represents sites' scores, ranging from 0 to 100. When present, empty bars represent an estimation of the score potentially achievable by a site by substituting missing data with an average value from the entire dataset.

3.3. Preliminary ranking results

The best performing sites of the comprehensive ranking procedure were, in descending order, Sites #12, #22, #25, #18, and #31 (Fig. 4, Tables SM–24). The same sites also occupy the top five GP rankings, but in a different order, and placed in the upper half of both the HSE and EP rankings.

Three sites are now detailed that cover the entire range of values within the input dataset, analysing the correlation between their different characteristics and their corresponding performance scores. The most promising site is #12, which obtained high scores in all rankings. It benefitted from favourable records in highly influential parameters such as the presence of dry gas as the hydrocarbon type, the absence of faults affecting the gas accumulation zone, few drilled wells, a multi-layered anticline structure, a Datum Depth of 1020 mssl, a sandstone reservoir, a Mean Porosity value higher than 25%, and Permeability Mode higher than 100 mD. Valuable database records in minor features, including free gas expansion as the main hydrocarbon production mechanism, a weak water influx with a subsequent low water production, and a small areal extension of the production site (2.5 km^2), further contributed to its high score, despite low values of temperature and salinity (around 55 °C and 0.5 mol/L). Site #40 achieved a mid-ranking position in the GP and comprehensive ranks, a lower position in HSE and a higher position in EP. Non-optimal records like the presence of wet gas as the accumulated hydrocarbon and the occurrence of faults edging the reservoir determined the intermediate score, as well as moderately low values of reservoir porosity (10.4%), permeability (11 mD), temperature, and salinity. However, positive aspects like the presence of a single well, a multi-layered anticline reservoir, a sandstone lithology and a Datum Depth of 722 mssl, contributed to the overall intermediate result. Site #48 placed at the bottom of all rankings due to several challenging features. Identified as light oil, the hydrocarbon type received the lowest score from the normalization process, as well as the carbonate reservoir lithology and its complex architecture, which is recorded as compartmentalized, fractured and karstified. The Faulting Description parameter highlighted numerous faults crossing an extended reservoir area, which is almost 35 km^2 wide and has 30 drilled wells. Additionally, the Datum Depth is very deep, measured at 5570 mssl. Positive records, such as a markedly high permeability related to the presence of fractures and high temperature due to depth, received maximum scores in the normalization process but were insufficient to balance the negatives.

In ranking scores, blank records are considered as zeros, resulting in a conservative assessment of the sites' efficiency. This approach assigns the lowest possible score to candidates with missing data, favouring better-characterized sites due to their lower exploration costs and uncertainties. In the potential scores, missing data were replaced with average values, offering a more optimistic view of the potential of less well-known sites. This secondary outlook allows decision-makers to differentiate between sites with poor scores due to actual deficiencies and those with poor scores due to missing data, potentially enabling the evaluation of further exploration for promising but less characterized sites. Regarding the missing data, note that the 27 screening parameters were chosen from the wider industrial dataset based on multiple criteria, including their record completeness. Nevertheless, exceptions are represented by the parameters of Rock Consolidation, Reservoir Texture, Surface Extension, and Water Salinity, whose data were missing in 26, 24, 12, and 11 sites out of 48, respectively. As a result, each studied site exhibits up to 3 missing records, except for sites #33, #42, and #43, each with 4 missing records out of 27, and Site #19, that has 7 blank records out of 27 and achieved the highest potential score. However, a linear correlation between potential score and the number of missing data is not present, as the potential score depends on the missing parameters' weights. For example, sites #42 and #43 (i.e., two sites that lack 4 records), achieved increases in their potential scores of 6.1 and 1.8, respectively, indicating that Site #42 lacks parameters of higher weights than Site #43.

3.4. Method refinement and site-screening results

To check the method, a blind test was conducted using a subset from another proprietary database, comprising four sites from North Africa that had already been characterized and ranked by Eni. In the initial ranking obtained with the present method, the top-ranked site did not match the existing ranking, shifting the order by one position (the rankings for the second, third, and fourth sites corresponded with previous evaluations). In fact, the best site exhibited favourable characteristics for UHS based on the considered parameters, but it was deemed a suboptimal option in the company's assessment due to its prolonged closure (which posed challenges from a feasibility point of view due to the possibility of flooding). This mismatch in the first position was considered unsatisfactory and highlighted the need to penalize sites considered a priori compromised due to specific unfavourable features. To address this, a 15% reduction in both screening and potential scores was introduced for sites located at excessive depths (i.e., >3500 mssl), and a more substantial 25% reduction was applied in the case of decommissioned production sites, as well as for fractured media reservoirs.

Penalties were chosen to address these issues because adjusting parameter weights to achieve the same result would have greatly reduced method resolution. This is because the new weight would need to be so large that its inclusion would reduce the relative importance of the other subgroup parameters (especially in smaller groups) given that weights are normalized to 100%. With this approach, Depth can be considered as a normal parameter that takes into account its impact on different geotechnical and economic issues, but with the additional potential to assign a 15% penalty where depths are excessive for hydrogen storage. The other adverse features are only considered in this stage and result in a 25% penalty. The calibration of these percentage values considered the operational input of the industrial partner, aiming

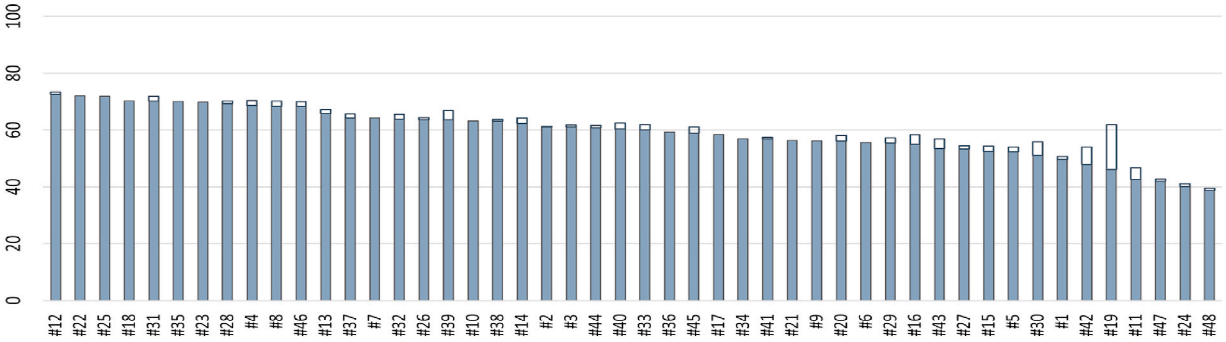


Fig. 4. Ranked bar chart showing the scores achieved by the sites (solid bars) and their potential scores (empty bars). Note that the horizontal axis lists site IDs ranging from 1 to 48, while the vertical axis represents sites' scores, ranging from 0 to 100.

to find a balance where penalties were high enough to address adverse characteristics without disproportionately impacting site rankings. The resulting penalties preserve method resolution while preventing the exclusion of penalized sites from the screening process.

To further check the introduction of penalties, a second blind test was conducted on a larger confidential dataset, which comprised 16 sites from North Africa (including the subset used in the first test). The result demonstrated a satisfactory match with an existing ranking provided by Eni (Fig. 5), yielding a Pearson correlation index of 0.75.

As expected, some differences in the ranking positions occur due to the different approaches used. Sites NA#4, NA#10, and NA#11 are the main outliers; however, it must be noted that these three sites are characterized by the lack of crucial information used in the current method. In particular, NA#10 only had 11 records out of 27, and thus despite having a mid-rank in the pre-existing ranking it placed last in the blind test (but with a high potential score). In addition, apart from site NA#10, NA#4 and NA#11 were the only sites in the North African dataset that lacked data about faults, a crucial parameter in the score calculation; this resulted in a difference of 3 and 4 positions between rankings, respectively. The exclusion of these sites results in a Pearson index of 0.93 for the remaining 13 reservoirs. This increase highlights the importance of consistent data inputs for an impartial ranking outcome, which might be indicated by anomalously high potential scores, as well as the effectiveness of the method in the right conditions.

By applying these two penalties to the large Italian dataset, a final ranking was produced (see Fig. 6, Tables SM–24) that incorporates the score reductions for those sites characterized by unfavourable conditions. For example, both Site #12 and Site #48 were penalized due to decommissioning, but while in the latter case it didn't vary the site position, with Site #48 retaining last, for Site #12 it caused a repositioning from top to mid-rank. Indeed, penalized sites are not excluded from the screening process, and cases like Site #12, that demonstrated good characteristics for UHS aside from the decommissioning status, might still be considered for future evaluations or alternative uses.

4. Summary and conclusions

The present article describes a new site-screening method to rank depleted and almost depleted hydrocarbon reservoirs for Underground Hydrogen Storage (UHS), with subsequent testing on a confidential dataset of 48 production sites from Italy provided by the energy company Eni. A set of 27 screening parameters was selected from a wider dataset and distributed amongst three site-assessment supergroups: i) health, safety and environment (HSE); ii) geotechnical performance (GP); and iii) economic performance (EP). Note that some parameters were assigned to more than one supergroup. Weights for each parameter, based on their impact on each supergroup theme, were defined using the Analytic Hierarchy Process (AHP) combined with expert opinions from both academia and industry collected using the Delphi technique. To standardize the diverse dataset formats, records were normalized into dimensionless scores ranging from 0 to 1 based on literature insights and operational considerations. These weights and normalized records were then used to calculate individual scores for each supergroup as well as a comprehensive site-screening score that aggregates these sub-scores based on supergroup weighting. To assess the impact of missing data, the workflow was repeated using database averages in place of null values to produce potential scores. As a final step, penalties were applied to the comprehensive scores to address specific features that are particularly adverse for UHS feasibility, safety, and/or economics. In particular, a 15% penalty was applied when reservoir depth exceeded 3500 mssl and a 25% penalty was applied if the site was abandoned, flooded or had fractured-media reservoirs. To assess the reliability of the method, two blind tests were conducted on a smaller Eni dataset containing well-known sites from North Africa, the first involving a subset of the sites and the second using 16 sites. The results yielded a good match with the existing assessments performed by Eni on the same dataset.

The application of this method to the initial dataset produced multiple outputs and advantages. First, parameter hierarchization ensures a clear identification of the most important parameters, as defined by the operators. In this case, major screening criteria were the presence of faults, the kind of hydrocarbon in the reservoir, the onshore/offshore site location, the number of wells, the reservoir architecture, the depth of the reservoir, and its initial pressure. Second, the weighting process is transparent thanks to the use of the AHP surveys, which consist of pairwise comparisons between parameters that detail the reciprocal dominances assigned by the operators. Third, the calculation of individual HSE, GP, and EP scores provide decision-makers valuable insight into a site's potential as seen from different points of view. Finally, the primary outcome of the screening method is a ranking of sites that illustrates their overall UHS potential. This ranking is based on a set of scores derived from screening calculations and the application of penalties, with results from the large Italian database ranging from 29 to 72 out of 100. Penalties do not affect the HSE, GP, and EP scores, but serve as a filter in the final ranking that emphasize unsuitable sites for hydrogen storage.

As described above, the proposed methodology operates at different levels of detail. It allows one to quantify site performance based on specific criteria and provides a comprehensive screening score for UHS purposes, while at the same time assessing less well-characterized sites and a means for identifying challenging scenarios. This versatility makes it suitable for both preliminary screenings at the national or transnational scales and detailed assessments on smaller scales or preselected groups of candidates. Moreover, the integration of the Delphi technique and AHP allows one to consider and harmonize multiple points of view, using a proven weight calculation method that minimizes the chances of manipulation in the decision-making process. Due to these features, this methodology represents a valuable tool for decision-makers for an objective management of complex scenarios.

In its current configuration, the method was shown to be a highly efficient tool for the screening of sites for UHS, enabling their prioritization and thus the identification of a subset of promising alternatives among a wider range of candidates. To go beyond this screening stage, future implementations should consider additional parameters that

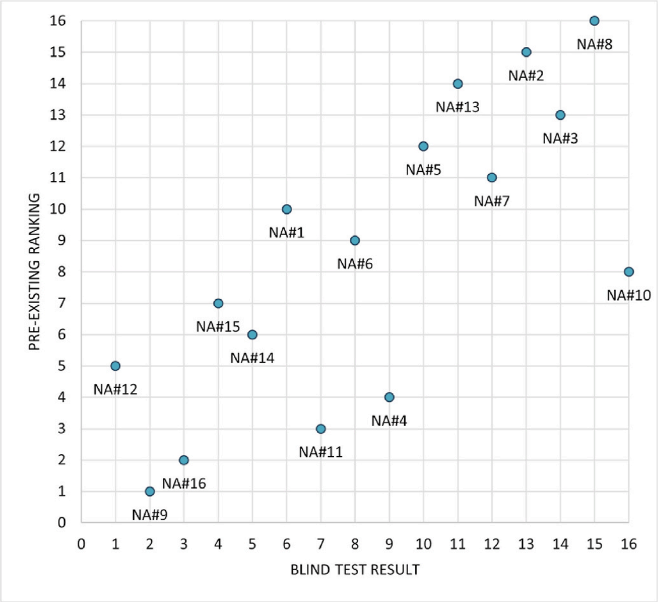


Fig. 5. Scatterplot that illustrates the outcomes of the second blind test using a proprietary dataset from North Africa. The plot compares site rankings provided by Eni (Y-axis) with results from the presented methodology (X-axis). Sites are coded for confidentiality.

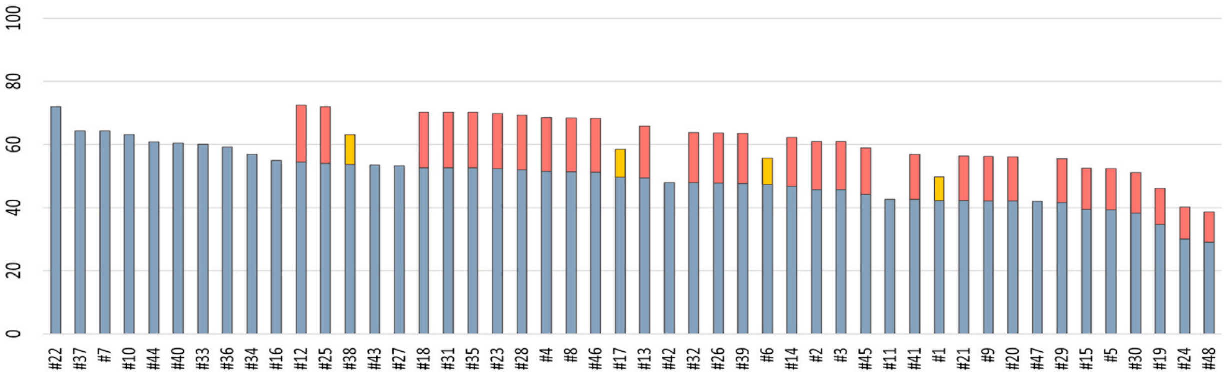


Fig. 6. Site ranking outcome of the complete screening procedure for the entire large Italian dataset. Blue bars represent the screening scores of sites including penalties, red bars represent the original scores of sites that received a major penalty (decommissioned sites and fractured-media reservoirs), and yellow bars represent the original scores of sites that received a minor penalty (reservoirs below 3500 mssl). Site IDs ranging from 1 to 48 are displayed in the horizontal axis, sites' scores are represented in a range from 0 to 100 in the vertical axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

were not addressed in the initial oil and gas production dataset. For instance, detailed assessments are recommended to explore the efficiency and characteristics of the caprocks, the site-specific microbial reactivities, and the degree of saturation of residual hydrocarbons. It should be highlighted, however, that the proposed methodology is customizable in terms of the number and types of screening parameters and evaluated sites, as well as the parameters' assigned weights and record normalization rules. This flexibility allows for such implementations, enabling the method to accommodate changes in screening purposes, stakeholder priorities, data availability, or advancements in research.

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CRediT authorship contribution statement

R.M. Ridolfi: Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization. **S. Azzaro:** Validation, Methodology, Data curation. **S.E. Beaubien:** Writing – review & editing, Methodology, Formal analysis. **A. Da Pra:** Validation, Methodology, Data curation. **M. Pontiggia:** Validation, Supervision. **S. Bigi:** 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.2024.08.291.

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