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# Criteria and workflow for selecting depleted hydrocarbon reservoirs for carbon storage

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## HIGHLIGHTS

- Hub scale storage requires large-scale screening using a multi-stage workflow.
- A quantitative, criteria-driven methodology allows for storage site selection.
- Technical, regulatory, economic, and environmental constraints are considered.
- Testing in the Gulf of Mexico identified 31 fields for further study.

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ABSTRACT

Carbon capture and sequestration (CCS) is playing a role in mitigating carbon emissions and that role is expected to grow dramatically with time. Clustering $CO_2$ sources and sinks through hubs is one way to achieve large-scale deployment of CCS and widespread decarbonization of the energy sector. A key element to the success of hub projects is finding a suitable sequestration site to store these combined emissions. In this study, a quantitative, criteria-driven methodology was developed to assess the potential suitability of depleted oil and gas reservoirs for carbon storage. The methodology utilizes a three-stage process that screens, ranks, and characterizes potential sites based on three categories: (1) capacity and injectivity optimization, (2) retention and geomechanical risk minimization, and (3) siting and economic constraints. Many potential sites are assessable using this methodology until an optimal depleted reservoir, or geographically adjacent set of reservoirs, is identified. The framework is designed to provide insights into the suitability of depleted reservoirs in a variety of different geological environments as well as to be adaptable to a project's specifications. Specifically, the criteria-driven workflow was applied to fields in the Gulf of Mexico and screened 1,317 fields to identify 10 clusters of 31 fields for further assessment and then ranked those fields and clusters to identify the most suitable sites for secure storage.

## 1. Introduction

Carbon capture and sequestration (CCS), including utilization (CCUS), will play a significant role in mitigating carbon emissions and is a crucial technology for the decarbonization of the energy sector and hard-to-abate industrial sectors [55,60,74,80]. The 2015 Paris Agreement set a goal to reduce global greenhouse gas emissions to limit warming to 1.5 °C [38]. CCS is an essential option in many decarbonization scenarios to meet this climate goal [38,74]. As reported in the IEA's Sustainable Development Scenario, CCUS constitutes approximately 15% of the cumulative reduction in emissions compared with the Stated Policies Scenario [35]. The SDS estimates that the mass of $CO_2$ captured will increase from around 40 megatonnes (MT) per year of $CO_2$ today to around 10.4 gigatonnes (GT) in 2070 [35].

Clustering sources from large and small-scale industrial plants helps to achieve this widespread deployment. Some CCS infrastructure is shared, thus, reducing costs compared to each facility independently sequestering emissions [22,31]. CCS hubs would collect emissions from a capture cluster and transport those emissions to a storage site. These

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**Nomenclature**

| | |
|---|---|
| $A$ | reservoir area |
| $C$ | $CO_2$ capacity |
| $C_s$ | mass of $CO_2$ dissolved per unit volume of water |
| $c_t$ | compressibility |
| $h$ | reservoir thickness |
| $k$ | permeability |
| $M_{CO2t}$ | Mass of $CO_2$ |
| $Q$ | volumetric flow rate |
| $r$ | radius |
| $r_e$ | drainage radius |
| $R_f$ | recovery factor |
| $r_w$ | wellbore radius |
| $S_{or}$ | residual oil saturation |
| $S_w$ | water saturation |
| $S_{wir}$ | irreducible water saturation |
| $t$ | time |
| $V_{iw}$ | volume of injected water |
| $V_{pw}$ | volume of produced water |
| $\Delta P$ | pressure buildup |
| $\mu_w$ | water viscosity |
| $\mu_{CO2}$ | $CO_2$ viscosity |
| $\rho_{CO2}$ | $CO_2$ density |
| $\phi$ | reservoir porosity |

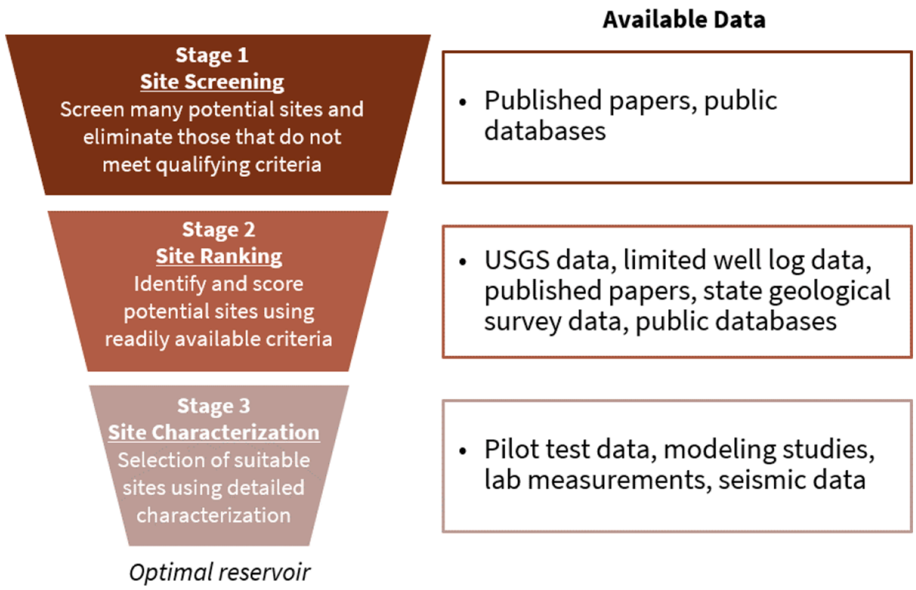


**Fig. 1.** Overview of the site selection workflow designed to select the most suitable site from a pool of potential storage reservoirs. The criteria-driven methodology has three main stages: site screening, ranking, and characterization.

hubs reduce costs through shared infrastructure, enabling the capture of small volume sources, reducing commercial risk for storage, enabling CCS in regions without access to suitable local storage, and enabling low carbon industrial production [31]. A key element to the success of these hub projects is finding a suitable sequestration site to store the combined emissions. Many existing projects and studies have focused on finding a storage site based on the location of a particular emissions source (i.e., source-sink matching) [16;17,25,43;48,49;69;71,83,84]. Many of these studies utilize Geographical Information Systems (GIS) to screen basins or large geographic areas near sources. They may include categories such as risk assessments, data availability, or infrastructure in their analysis or only focus on capacity [49,85]. However, we propose a regional exploration method that screens and ranks many potential sites for these hub scale projects and identifies an optimal storage site, or sites, to sequester a large quantity of $CO_2$.

Other studies have developed best practices or general approaches to selecting a site [19,20,36]; IPCC, 2005; [39,57]. Many prior studies do not identify specific quantitative metrics or only indicate positive and cautionary indicators. Many of these prior studies contain a mixture of objective threshold metrics and subjective descriptive standards for the criteria set forth. Screening criteria and metrics are inconsistent across studies. This may create confusion in the case of subjective criteria, resulting in conflicting site evaluations and making final project decisions difficult. While these studies help identify potential regions or basins that might be suitable, a more detailed approach is needed to select a specific storage site.

CCS requires a long-term storage site capable of storing $CO_2$ for thousands of years, or more, and having adequate capacity and injectivity. $CO_2$ can be stored in a variety of sedimentary formations such as depleted oil and gas reservoirs, deep coal seams, and saline formations, as well as other geological structures and media such as basalts, salt caverns, oil or gas shales, and abandoned mines [37]. Depleted oil and gas reservoirs are an excellent storage option for CCS because the geology and geologic conditions have trapped hydrocarbons and prevented migration upward for millions of years [87]. Likewise, these fields have generally been extensively studied and have data such as well logs, pre and post-production pressures, production history, and reflection seismic available for analysis.

Additionally, many factors influence the suitability of a geological storage site ranging from the geology and geomechanical environment to injectivity and capacity parameters to the economics and social and political frameworks [50]. Previous studies that have developed site screening criteria for depleted oil and gas fields reflect the broad expertise of the authors and are not comprehensive in presenting holistic criteria that address all technical, regulatory, political, economic, environmental, and social considerations [3,23,34,44,45,63,64;70]. All

**Table 1**
Site screening criteria for depleted reservoirs. Detailed descriptions of each criterion can be found in the Supplementary Material.

| Category | Criteria | Disqualifying Threshold |
|---|---|---|
| Capacity and Injection Optimization | Depth to Top of Formation | <800 m |
| | Permeability | <10mD |
| | Porosity | <10% |
| | Reservoir Thickness | <10 m |
| | Minimum Storage Capacity | < the minimum capacity needed for project |
| Retention and Geomechanical Risk Minimization | Secondary Confining Units | No secondary confining unit |
| | Top Seal Thickness | <25 m |
| | Active/Inactive Faulting | Faults active in the Quaternary distance from closest injection well: <2km |
| | Earthquake Record | $M \geq 3$ (epicenter < 10 km) & $M < 3$ (epicenter < 5 km) to pressure front |
| | Bottom Seal/potential for pressure transmission to the basement | No bottom seal |
| | Production from a reservoir below the storage interval | Yes |
| Siting and Economic Constraints | Sensitive Habitats for depleted fields that are inactive | Critical wildlife habitat for certain species and wilderness study areas |
| | Population Density for depleted fields are that are inactive | > 75 people per $km^2$ |
| | Restricted Lands for depleted fields that are inactive | National landmarks, conservation lands, military installments, American Indian Lands, Federal Lands and State Lands |
| | Maximum Depth to Top of Formation | ≥ 10,000 ft (3,048 m) |
| | Water Depth (if offshore) | >500ft (152.4 m) |

these factors need to be considered in the evaluation criteria. Developing a consistent methodology to screen potential geological storage sites is integral to the large-scale deployment of CCS technologies to ensure safe, secure, and economic sequestration. Many of these previous studies also focus on a particular geographic area or a specific project rather than developing a generalizable set of criteria that can be applied in any area of interest [3,34,63;70,79].

As a result, there is a need for a comprehensive suite of site selection criteria and a scoring system. Using a multi-stage criteria-driven approach is essential for the large-scale screening of potential storage sites. Our methodology is adaptable to various regions and projects and comprehensively presents criteria that address all technical, regulatory, political, socio-economic, and environmental considerations. The novelty of this work is the development and testing on real-world data of a comprehensive, objective site selection methodology and scoring system. With this study, we introduce consistency in evaluation for future geological CCS projects that utilize depleted oil and gas reservoirs, thus improving recognition of site suitability and enhancing decision making. This paper presents the methodology and criteria developed for the selection of a depleted hydrocarbon reservoir for carbon storage. Then, this criteria-driven workflow and scoring system is applied to a case study in the Gulf of Mexico consisting of 1,317 fields.

## 2. Methodology

The criteria-driven process involves the selection of a suitable site, or sites, based on general and project-specific requirements (e.g., large capacity and injectivity, low leakage or induced seismicity risk, low costs, and low siting risk) that can be applied to a specific project in a variety of locations and geological environments. The design of this workflow allows sites to be compared systematically while also adaptable to the needs of a particular project.

The methodology is organized into three stages of site evaluation, ranging from initial site screening to site-specific characterization, leading to the selection of the most suitable sites (Fig. 1). The workflow utilizes information generally available in public databases, geological surveys, or storage atlases for the site screening and ranking stages. Additional information, simulations, and data may need to be acquired or performed to select the optimal site in the site characterization stage. The data required at each stage and the complexity of analysis increase while the number of sites evaluated decreases.

1. *Site Screening* is the first stage in which many potential sites are eliminated if they do not meet a qualifying threshold based on capacity and injectivity, geological, economic, and siting considerations. The sites that meet these qualifying criteria move to Stage 2, site ranking.
2. *Site Ranking* scores and ranks the sites that met the thresholds in the site-screening stage. These sites receive a normalized score between zero and one for every criterion. The data quality and availability are assessed in this stage and receive a confidence score. Each site receives a technical score that combines the capacity and injectivity optimization and retention and geomechanical risk minimization criteria scores, a siting and economic constraints score, and a combined overall score. The user can assign a weight to each criterion based on the most important parameters for their project. The data confidence score and criteria weightings are factored into the category and total scores. The highest-ranking sites move onto the site characterization stage.
3. *Site Characterization* is the final stage where the top-ranking sites from Stage 2 are analyzed in detail so that the user may determine the most suitable site. Additional data may need to be acquired at this stage (e.g., seismic, pilot test data), or computational and experimental studies may need to be performed to characterize each reservoir.

The criteria are divided into three major categories based on the priority objectives [62–63,84]. These categories address the areas of concern related to the geological injection and storage of $CO_2$: (i) Capacity and Injection Optimization, (ii) Retention and Geomechanical Risk Minimization, (iii) Siting and Economic Constraints. Detailed write-ups for all criteria presented are presented in Appendix C.

### 2.1. Capacity and injection optimization

A selected site needs to have sufficient capacity to store the required volumes of $CO_2$ with favorable injectivity. Injectivity is an essential property of geologic formations that defines both the technical and economic suitability of a site for $CO_2$ storage [84]. Injectivity characterizes the ease with which a fluid is injected into a geological formation. The injectivity index for a formation is typically represented by Eq. (2.1) [44,46].

$$I = \frac{Q}{\Delta P} = \frac{2\pi kh}{\mu \ln \frac{r_e}{r_w}} \tag{2.1}$$

where $I$ is the injectivity index, $k$ is the permeability, $Q$ is the injection rate, $\Delta P$ is the injection pressure buildup, $h$ is the thickness, $\mu$ is the viscosity, $r_e$ and $r_w$ represent the drainage and wellbore radius, respectively. We assume $CO_2$ is injected as a supercritical fluid into the reservoir. Studies have found that $CO_2$ behaves similar to an incompressible fluid near the critical point, particularly when viscous forces dominate, such as during injection near the well [1,40,81]. The extent of our use of Equation (2.1) is to show that the permeability and thickness

**Table 2**
Stage 2 site ranking criteria for suitability evaluation.

| Category | Criteria | 1 (worst) | 2 | 3 | 4 | 5 (best) |
|---|---|---|---|---|---|---|
| Capacity and Injection Optimization | Compartmentalization | Numerous small (<10% the size of the project) compartments with separate pressure regions | 5–10 potential compartments | 3–5 Potential compartments | 2–3 Potential or confirmed compartments | No compartments |
| | Depth of Top of Formation | 800–1000 *m* | Deep (>3,000 m) | 2,000–3,000 *m* | 1,000–2,000 *m* | |
| | Permeability | 10–20 mD | 20–50 mD | 50–100 mD | 100–500 mD | >500 mD |
| | Porosity | 10–15% | 15–20% | 20–25% | >25% | |
| Retention and Geomechanical Risk Minimization | Buoyancy pressure difference between the hydrocarbon column and expected $CO_2$ plume height | Equal | | 2x greater | | >2x greater |
| | Stacked Reservoir/ Seal Pairs | 1 | | 2 | | 3+ |
| | Trap Style | Fault dependent trap (normal) | | Stratigraphic, Rollover anticline into growth fault, faulted anticline | | Double-plunging Anticline (Dome) |
| | Degree of Faulting | Extensively faulted | | Moderately faulted | | Limited faulting |
| | Presence of Quaternary Faults at Reservoir Depth | 2–5 km from closest injection well | | 5–10 km from closest injection well | | >10 km from closest injection well |
| | Density of Existing/ Abandoned Wells | >8 wells/km$^2$ | 6–7 wells/km$^2$ | 4–5 wells/km$^2$ | 2–3 wells/km$^2$ | <1 well/km$^2$ |
| | Age of Existing/Abandoned Wells (*US) | Pre- 1930 s | 1930–1952 | 1952–1974 | 1974 to present | |
| | Previous Resource in Reservoir | Depleted Oil Reservoir | | Depleted Oil + Gas Reservoir | | Depleted Gas Reservoir |
| | Max plume pressure resulting on caprock (as best can be determined from existing data) | 0.9x caprock fracture pressure | | 0.8x caprock fracture pressure | | < 0.8x caprock fracture pressure |
| | Reservoir Current Pressure | Close to initial reservoir pressure or severely depleted below the critical pressure (7.3 MPa) | | | | Sufficiently depleted that can accommodate injected $CO_2$ below the initial pressure |
| | $CO_2$ Density | <300 kg/m$^3$ | 300–500 kg/m$^3$ | 500–700 kg/m$^3$ | >700 kg/m$^3$ | |
| Siting and Economic Constraints | Local Public Support | Little to None | | Moderate | | High |
| | Regulatory Framework | Unclear/Not established | | Moderately clear/established | | Very clear and established |
| | Policy Support for technology | Little to None | | Moderate | | High |
| | Economies of scale associated with the size of the $CO_2$ source | 1 MT/yr | 3.2 MT/yr | 6 MT/year | 15 MT/yr | |
| | Proximity to Sources | >100 km | 50 km – 100 km | 10–50 km | <10 km | Co-located |
| | Permitting | No other permitted CCS sites in state/region and state/region not perceived to be supportive & have none of these supportive measures | | No other permitted CCS sites in state/region but state/ region perceived to be supportive of CCS projects (e.g., primacy, unitization, clarity on pore space ownership, long-term liability laws)- only has some of these measures | | Other CCS sites permitted in state/ region and have all supportive measures |
| | Existing $CO_2$ Pipeline | None | | | | Yes |

are proportional to injectivity for screening and ranking. Understanding the injectivity of a site is needed for initial planning of the number of wells, and their design, which is a key cost driver in project development [57]. A minimum permeability for a site is 10 mD to ensure sufficient injectivity and reduce the number of wells needed [21]. A minimum reservoir thickness of 10 m is necessary to monitor and verify the plume footprint over the life of the project and in the post-injection phase using seismic data (Table 1). In Stage 2, a high permeability is desirable, resulting in high injectivity (Table 2). Injectivity is also a function of the reservoir thickness.

The EPA regulates the maximum allowable surface injection pressure (MASIP) through the Underground Injection Control (UIC) Program and effectively places an upper limit on injectivity to ensure no fracturing or propagation of existing fractures occurs [57]. In general, sites with high injection pressures require more wells thereby increasing the cost of a project. Additionally, the higher the injection pressure, the greater likelihood for brine and $CO_2$ migration through the seal. This issue is examined in greater detail in the leakage risk minimization section.

Another essential metric, storage capacity, measures the quantity of $CO_2$ stored at a particular site. The capacity is proportional to the porosity of a site, as seen in Eq. (2.2) for depleted oil reservoirs and Eq. (2.3) for oil and gas reservoirs [8,44] as.

$$M_{CO2t} = \rho_{CO2} \bullet (1 - S_{or} - S_{wir}) \bullet \phi + S_{wir} \bullet \phi \bullet C_s \tag{2.2}$$

$$M_{CO2t} = \rho_{CO2} x \left[ R_f x A x h x \phi x (1 - S_w) - V_{iw} + V_{pw} \right] \tag{2.3}$$

where $M_{CO2t}$ is the mass of $CO_2$, $\rho_{CO2}$ is density of $CO_2$, $S_{or}$ is the residual oil saturation, $S_{wir}$ is the irreducible water saturation, $\phi$ is the porosity, $C_s$ is the mass of $CO_2$ dissolved per unit volume of water, $R_f$ is the recovery factor, $A$ is reservoir area, $S_w$ is water saturation, and $V_{iw}$ and $V_{pw}$ are the volumes of injected and produced water, respectively. The results of this study are sensitive to capacity estimates, which will be discussed further in the discussion section. In both Equation (2.2) and Equation (2.3), as the porosity increases, the amount of $CO_2$ stored in a reservoir increases. In Stage 1, sites are screened for a minimum porosity of 10%, that is needed to sequester sufficient amounts of $CO_2$ (Table 1). In Stage 2, sites with larger porosities receive a higher score (Table 2). $CO_2$ storage capacity depends not only on the properties of the reservoir rock, but also on the nature of its boundaries [20].

Pressure-depleted compartmentalized reservoirs bring a host of issues, including the need for more wells to achieve desired $CO_2$ injection volumes, potential reservoir stress changes, and rapid pressure buildup during injection. Therefore, sites with fewer pressure-separated compartments receive higher scores than those with numerous compartments during site ranking.

Under normal pressures and temperatures, $CO_2$ is supercritical at depths greater than 800–1,000 m and provides the potential for efficient utilization of storage space and improved storage security (IPCC, 2005; [75]. As a result, sites less than 800 m deep are eliminated during site screening (Table 1). $CO_2$ density increases with depth until about 1,000 m then becomes nearly constant below that depth [6]; IPCC, 2005). As $CO_2$ density increases, the storage efficiency increases, and the buoyancy force decreases, providing more storage security (IPCC, 2005). Therefore, during site ranking, sites are assigned the highest score at depths between 1,000 and 2,000 m. As sites get deeper, the drilling and completion costs increase [88], and, generally, rocks are more cemented and have lower porosity [26]. For those reasons, very deep sites (>3, 000 m) get the second-lowest score (Table 2).

### 2.2. Retention and geomechanical risk minimization

The leakage and geomechanical risk minimization criteria examine characteristics of the top seal, possible leakage pathways such as faults, and other hazards to the storage site to highlight potential risks to the storage security of the site.

The top seal of a storage site is a primary method to ensure storage security. In site screening, a minimum top seal thickness of 25 m is established based on the ability to image seismically a discrete seal interval outside the limits of the original hydrocarbon accumulation. A site with a maximum (at trap crest) original hydrocarbon-brine buoyancy pressure difference greater than twice the expected $CO_2$-brine buoyancy pressure is the most desirable and receives a higher score during site-ranking. Additionally, the EPA has established minimum siting criteria for $CO_2$ storage that apply to Class VI wells and requires a secondary confining unit [40 CFR 146.83]. Therefore, sites without a secondary confining unit are disqualified in Stage 1. Stacked reservoir/seal pairs refer to potential reservoir and seal rocks overlying the primary injection reservoir and its immediate top seal. Most published CCS criteria include reservoir-seal redundancy to ensure injected $CO_2$ does not migrate from the primary reservoir into overlying potable aquifers or to Earth's surface [18,20,23,36]. The probability of such migration reduces significantly as more potential secondary reservoir/seal pairs are identified in the sedimentary section overlying the primary reservoir/seal pair. Therefore, in Stage 2, sites with more stacked reservoir/seal pairs receive a higher score. Another method to address retention risk is the trap style of the site. All petroleum traps, structural or stratigraphic, must have four directions of closure in order to retain buoyant hydrocarbons [14]. In Stage 2, trap types are ranked based on closure complexity that affects the quality of trap definition and its impact on storage security.

The current reservoir pressure and maximum plume pressure are also important indicators of the ability to inject $CO_2$ without exceeding 90% of the fracture pressure of the injection zone as instructed by the EPA for Class VI wells (EPA 2010, §146.88). The previous resource is also a helpful indicator for site selection. Depleted gas reservoirs usually have less free water and residual gas that allows for higher storage capacity for $CO_2$ and limited corrosion of well casing and degradation of the well cement [23]. Gas fields usually have lower pressure at the end of their lifetime, making them desirable for carbon storage [23].

Earthquakes, nearby faults, and abandoned wells can also threaten the storage security of a site. A site that has experienced a nearby earthquake should be ruled out in addition to sites that are near recently active faults. The pressure buildup from $CO_2$ injection may induce slip along a recently active fault [67]. Additionally, faults in the vicinity of an injection well may allow $CO_2$ to escape into overlying strata [30]. Sites with extensive faulting or nearby quaternary faults receive lower scores during site ranking. A bottom seal is also necessary to limit pressure transmission to the basement rock, reducing the risk of induced seismicity from injection at a site [82]. A bottom seal also reduces the potential for leakage away from the site. Abandoned or existing wells may also present a leakage risk. A well that goes through the candidate storage unit breaches the natural confining zone and could result in leakage of $CO_2$ away from the site. Therefore, sites with production below the storage site should be disqualified during the screening process. If a site has existing or abandoned wells, the density and the age of those wells will influence the likelihood of $CO_2$ leakage. Large well densities and numerous old wells may result in a greater risk of $CO_2$ migration away from the site; therefore, those sites receive lower scores during site ranking.

### 2.3. Siting and economic constraints

While the technical suitability of a site relies more heavily on the categories mentioned above, the economic feasibility of a site can make a site unfavorable to develop. Many challenges may arise when choosing a site in a densely populated area, such as pore space rights and ownership, access and permission to perform site characterization studies, and possible high land values [57]. Using the work from [67], the cutoff of 75 people per $km^2$ is used as a screen to eliminate sites during site screening. Sites should be avoided in sensitive habitats or restricted lands [57]. Local public support, regulatory framework, and policy incentives for CCS can also influence the ability for a project to be developed [4]. Permitting can slow projects down and increase costs. The support of the public both locally and nationally and the regulatory framework and policy support can also impact the success of a potential site.

For offshore sites, sites in shallow water depths are the most economical due to the relatively low cost of jack-up platforms that are used for water depths less than 500 ft (152.5 m) deep [3;47]. Drilling and completion costs increase with depth. So, sites>10,000 ft (3,048 m) deep should be eliminated during the site screening stage to keep well costs per meter less than $1,000 [88]. The distance between the sources and sequestration sites and the size of sources can influence project costs due to the transportation and infrastructure needed [56;65].

## 3. Application of the methodology and criteria in the Gulf of Mexico

The Gulf Coast of the United States has the nation's largest volumetric concentration of industrial $CO_2$ emissions and these sources are aggregated in industrial clusters that allow combining emission streams to achieve economies of scale [54]. Additionally, the Gulf of Mexico is one of the most geologically explored basins due to prolific hydrocarbon accumulations and this is a strong indicator of favorable large-volume $CO_2$ storage [54]. According to the Bureau of Ocean Energy Management (BOEM), there are over 13,000 oil and gas sands in federal waters in the Gulf of Mexico, many of which could be used for storage [15]. Due to this history of hydrocarbon production, there are abundant and high-quality geologic datasets for the region; however, given the region's size and quantity of potential sites, assessing the suitability of these reservoirs poses a challenge. Therefore, the Gulf of Mexico provides an optimal opportunity to apply the methodology described above.

For this analysis, the BOEM dataset of oil and gas sands in federal waters in the Gulf of Mexico was used. The dataset includes information

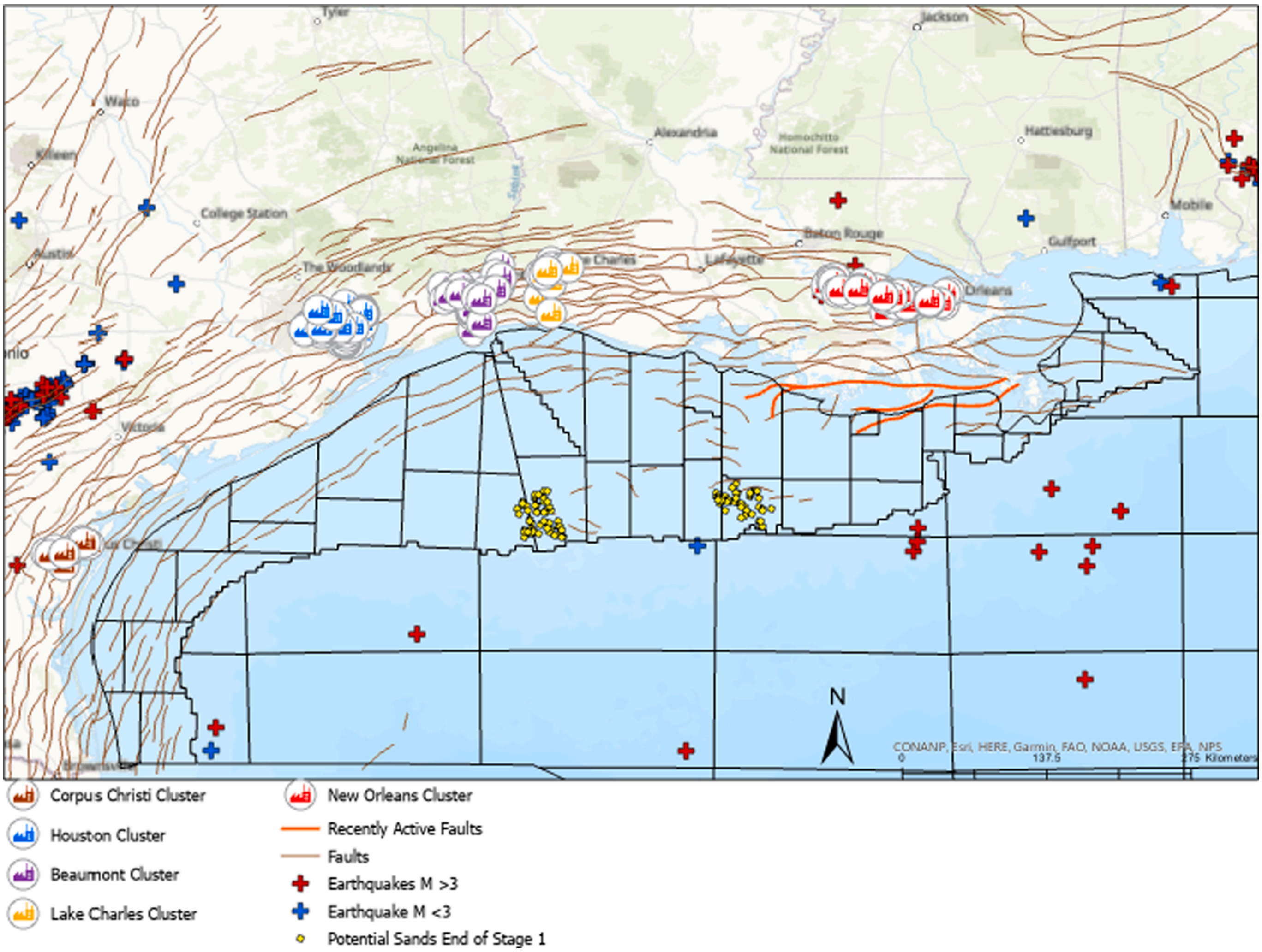


**Fig. 2.** Potential $CO_2$ storage sands at the end of Stage 1. Potential clusters of onshore emitters are indicated.

sand by sand about production and reserves, wells, and geological characteristics (e.g., permeability, porosity, thickness, water saturation, initial pressure, initial temperature, trapping, and structure information). Detailed write-ups for all criteria presented are presented in the Supplementary Information.

### 3.1. Stage 1: Site screening

We applied criteria from the capacity and injectivity optimization, retention and geomechanical risk minimization, and siting and economic constraints categories to 1,317 fields in the Gulf of Mexico and 1,286 fields were screened out in Stage 1 (Fig. 2).

#### 3.1.1. Capacity and injection optimization

13,380 sands making up 1,317 fields were screened in Stage 1 using the criteria listed in Table 1. Applying the Stage 1 criteria for depth of the top of formation, permeability, porosity, and reservoir thickness reduced the number of potential sands to 2,629. Most sites eliminated were thin sands with a thickness of less than 10 m. A few shallow sands were eliminated as well. Formations in the Gulf of Mexico generally have high permeability and porosity, so only a handful of sites were eliminated due to low permeability; none were eliminated due to low porosity. The storage capacity for each sand was calculated using CSLF-Proposed Methodology for oil and gas reservoirs [8]. This project aims to store 10 million tons (MT) of $CO_2$ per year for 20 years. Because many of the potential sites are in close proximity, we clustered fields that are within 10 km of each other. The capacity of each cluster was calculated as a sum of the individual sand's capacity that make up that cluster. Clusters with a capacity less than 200 MT of carbon storage were eliminated because this project aims to store 10 MT/yr for 20 years. Because the Gulf Coast hosts a large concentration of emission sources, this cut-off of 200 MT is feasible. However, different projects and locations would use a different capacity threshold in Stage 1 that is specific to that project's objectives and the availability of emission sources.

#### 3.1.2. Retention and geomechanical risk minimization

To determine if there are secondary confining units, we looked for evidence in literature studies of a regional seal above the sands that could act as a barrier to any potential vertical migration of $CO_2$ away from the site. For example, Galloway et al. [29] identified Miocene-aged regional seals off the Texas coast [29]). Robulus "E" caps the Miocene. The Middle Miocene is capped by a transgressive shale Textularia stapperi, Lower Miocene 1 and 2 are bounded by Marginulina ascensionensis (Marg A) and Amphistegina chipolensis (Amph B), respectively [29,73]. The potential sites along the Texas coastline are all Miocene-aged; therefore, we identified multiple regional seals in the Miocene that could be secondary confining units depending on the depth of the potential site. The Amph B seal net-mudrock isopach in Offshore Texas State Waters averaged 303 m and ranged from 6 to 1,370 m [52]. This exceeds the minimum top seal thickness in Stage 1 of 25 m although as more data is acquired in later stages the top seal thickness for sites further from the coastline will need to be verified.

**Table 3**
Example site ranking scorecard for a site in the Gulf of Mexico. Green shading indicates a high score of 1, red indicates a low score, and intermediate scores are shaded pink.

| Category | Criteria | 1 (worst) | 2 | 3 | 4 | 5 (best) | Data Confidence Score | Weight |
|---|---|---|---|---|---|---|---|---|
| Capacity and Injection Optimization | Compartmentalization | 1/5 | 2/5 | 3/5 | 4/5 | 5/5 | Low | 0.07 |
| | Depth of Top of Formation | 1/4 | 2/4 | 3/4 | 4/4 | | High | 0.04 |
| | Permeability | 1/5 | 2/5 | 3/5 | 4/5 | 5/5 | High | 0.09 |
| | Porosity | 1/4 | 2/4 | 3/4 | 4/4 | | High | 0.06 |
| Retention and Geomechanical Risk Minimization | Stacked Reservoir/ Seal Pairs | 1/5 | 2/5 | 3/5 | 4/5 | 5/5 | High | 0.04 |
| | Trap Style | 1/5 | | 3/5 | | 5/5 | High | 0.04 |
| | Degree of Faulting | 1/5 | | 3/5 | | 5/5 | Low | 0.09 |
| | Presence of Quaternary Faults at Reservoir Depth | 1/5 | | 3/5 | | 5/5 | Low | 0.10 |
| | Density of Existing/Abandoned Wells | 1/5 | 2/5 | 3/5 | 4/5 | 5/5 | High | 0.09 |
| | Age of Existing/Abandoned Wells (*US) | 1/4 | 2/4 | 3/4 | 4/4 | | High | 0.09 |
| | Previous Resource in Reservoir | 1/5 | | 3/5 | | 5/5 | High | 0.06 |
| | Max plume pressure resulting on caprock (as best can be determined from existing data) | 1/5 | | 3/5 | | 5/5 | High | 0.06 |
| | $CO_2$ Density | 1/4 | 2/4 | 3/4 | 4/4 | | High | 0.05 |
| Siting and Economic Constraints | Local Public Support | 1/5 | | 3/5 | | 5/5 | High | 0.15 |
| | Regulatory Framework | 1/5 | | 3/5 | | 5/5 | High | 0.20 |
| | Policy Support for technology | 1/5 | | 3/5 | | 5/5 | High | 0.15 |
| | Economies of scale associated with the size of the $CO_2$ source | 1/4 | 2/4 | 3/4 | 4/4 | | High | 0.10 |
| | Proximity to Sources | 1/5 | 2/5 | 3/5 | 4/5 | 5/5 | High | 0.10 |
| | Permitting | 1/5 | | 3/5 | | 5/5 | High | 0.14 |
| | Existing $CO_2$ Pipeline | 1/5 | | | | 5/5 | High | 0.15 |

U.S. Geological Survey (USGS) data was used in conjunction with previous studies to identify recently active faults or faults active in the Quaternary period. For example, segments of the Baton Rouge, Golden Meadow, Theriot, Leeville, and Venice fault zones were active through the Pleistocene period and modern times [28]. Other fault zones, including Lake Hatch and Penchant, have experienced surface effects of fault movement that appear to be continuing [28]. The Gulf of Mexico has many growth and normal faults. From the data available from USGS, the faults in the Gulf of Mexico were loaded into GIS [78]. We eliminated sands within 2 km of those recently active faults thereby removing 65 sands [78].

USGS earthquake data was used to evaluate the distance between sands and earthquakes. Using the criteria that sites within 10 km of an earthquake greater than a magnitude 3 are eliminated, one site was removed [77]. There are no sands within 5 km of an earthquake less than a magnitude 3.

The final criterion in this category is production from a reservoir below the storage interval. By examining the dataset, there are no actively producing sands directly below a depleted sand. Application of this criterion does not eliminate any sands from our selection.

#### 3.1.3. Siting and economic constraints

Removing sites in a water depth>500 ft (152.4 m) eliminated 555 sands in deep water. The restricted lands along the Gulf Coast, according to the USGS, are within state waters. So, application of this criterion does not eliminate any of our sands in federal waters [76]). A large portion of the Gulf of Mexico is a Habitat Area of Particular Concern (HAPC) for Bluefin Tuna and a few areas are HAPCs for coral [58]. Most of this area, however, is off the continental shelf and is in deeper water than most of our prospective sites. Further, HAPCs do not convey restrictions or protections on an area; instead, they increase study and mitigation planning compared to surrounding areas [58]. Because our data is offshore, none of the sites have a population density>75 people per square kilometer. After eliminating sites deeper than 10,000 ft (3,048 m), 10 clusters made up of 31 fields remain and move to site ranking (Fig. 2).

### 3.2. Stage 2, site ranking

The fields within the ten clusters that meet the qualifying criteria in Stage 1 move on to Stage 2, site ranking, using the criteria in Table 2. In this case study, the Stage 2 criteria were applied on the sand and field level. A capacity-weighted average was used to calculate the average score for each cluster. The highest-ranking cluster moves on to Stage 3. Detailed criteria descriptions and calculations are found in the Supplementary Information.

#### 3.2.1. Capacity and injection optimization

Three of the four capacity and injection optimization criteria were applied on the sand level: depth to the top of the formation, permeability, and porosity. These three criteria are readily available in the BOEM dataset for each sand. An average of the underlying sand scores was used to calculate the field score for each criterion. Compartmentalization was assessed on the field level using 2D seismic data from the GOMsmart dataset [32].

#### 3.2.2. Retention and geomechanical risk minimization

Nine of eleven criteria in this category could be applied to all sites. The number of sands, trap style, and previous resource was provided for each field in the BOEM dataset. As seal data and stratigraphy for each field were unavailable, the number of sands was used to score each field. If the field had greater than three stacked reservoir/seal pairs, the probability of retention at desirable depths approaches 100% and, therefore, is the most desirable characteristic. Another method to address retention risk is the trap style of the site. All structural or stratigraphic petroleum traps must have four closure directions to retain buoyant hydrocarbons (Biddle & Wielchowsky, 1994). The BOEM dataset also provided the initial reservoir pressure and temperature. The

**Table 4**
Stage 2, site ranking, with average field scores for each field and capacity-weighted average cluster score. The highest-ranking cluster is Cluster 6. All clusters are highly prospective as seen by the small spread in average cluster score.

| Cluster 1 | | Cluster 2 | | Cluster 3 | | Cluster 4 | | Cluster 5 | | Cluster 6 | | Cluster 7 | | Cluster 8 | | Cluster 9 | | Cluster 10 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| EI330 | 0.62 | EI292 | 0.60 | EI333 | 0.60 | EI351 | 0.66 | EI306 | 0.68 | WC617 | 0.70 | SM142 | 0.63 | HI330A | 0.67 | WC587 | 0.58 | EI361 | 0.58 |
| EI292 | 0.60 | EI287 | 0.67 | EI292 | 0.60 | EI330 | 0.62 | EI292 | 0.60 | WC587 | 0.58 | EI330 | 0.62 | HI309A | 0.64 | HI309A | 0.64 | EI330 | 0.62 |
| EI333 | 0.60 | EI288 | 0.73 | EI330 | 0.62 | EI341 | 0.59 | EI296 | 0.60 | WC607 | 0.64 | EI333 | 0.60 | HI313A | 0.74 | HI330A | 0.67 | EI351 | 0.66 |
| EI351 | 0.66 | EI306 | 0.68 | EI335 | 0.60 | EI342 | 0.61 | | | WC615 | 0.68 | EI335 | 0.60 | HI327A | 0.71 | WC540 | 0.65 | | |
| EI361 | 0.58 | EI330 | 0.62 | SM128 | 0.55 | EI361 | 0.58 | | | WC618 | 0.67 | SM128 | 0.55 | HI368A | 0.70 | WC547 | 0.69 | | |
| SM142 | 0.63 | EI333 | 0.60 | SM142 | 0.63 | EI385 | 0.56 | | | WC635 | 0.74 | | | HI370A | 0.66 | WC589 | 0.67 | | |
| | | | | | | | | | | WC639 | 0.70 | | | WC587 | 0.58 | WC617 | 0.70 | | |
| | | | | | | | | | | | | | | WC589 | 0.67 | | | | |
| | | | | | | | | | | | | | | WC615 | 0.68 | | | | |
| *Capacity-weighted average cluster score:* | | | | | | | | | | | | | | | | | | | |
| *0.61* | | *0.62* | | *0.61* | | *0.60* | | *0.61* | | *0.65* | | *0.61* | | *0.63* | | *0.64* | | *0.61* | |

reservoir pressure and temperature were used to calculate the $CO_2$ density in the reservoir using the online Span and Wagner equation of state calculator from the US National Institute of Standards and Technology [66].

Abandoned wells are another potential source of migration away from the site. The density and age of abandoned or existing wells influence leakage risk. To assess the risk of these legacy wells, a storage security calculator (SSC) from Alcalde et al. [2] was used to estimate the percent of $CO_2$ leaked for different densities of wells per square kilometer in a well-regulated environment. Using the IPCC [37] guidance that 99% of $CO_2$ stored should be retained in 1,000 years to be an effective mitigation tool. Based on the SSC cumulative leakage estimates and the IPCC guidance, we determined that a well density greater than 8 wells/km$^2$ would result in more than 1% cumulative $CO_2$ leaked in 1,000 years in a well-regulated environment. Therefore, well densities of 8 wells/km$^2$ or greater receive the lowest score. GOMsmart provided information about wells in each field and was used to calculate the number of wells and area of each field block [32]. The age of the wells also provides information on the leakage risk of $CO_2$ to the surface. Numerous studies of reservoirs with abandoned wells that are repressurized by $CO_2$ have illustrated the potential of leaks [10–11,42,51]. In the United States, regulations on cementing and plugging wells have evolved in the past century. Therefore, the more recent the well, the higher the score it receives. The weighted average age of the wells in a field was used to score this criterion.

The maximum plume pressure resulting on the caprock can be approximated using Theis' solution [72]. Because the highest pressure is close to the injection well, we use the semi-log approximation of the Theis solution (Eq. (3.1)):

$$\Delta p = \frac{Q\mu_w}{4kh\pi}\left(\ln\left(\frac{4kt}{\phi\mu_w c_t r^2}\right) - 0.5772\right) \tag{3.1}$$

where $c_t$ is the compressibility, $r$ is the radius, and $t$ is the time. The assumptions made for this calculation are found in Appendix A. The fracture pressure of the caprock was approximated using Equation (3.2) from [86]:

$$0.8*\left(23\frac{MPa}{km}*(top\ of\ reservoir\ depth(km) + h(km))\right) = fracture\ pressure(MPa) \tag{3.2}$$

where 23 MPa/km is an assumed overburden gradient, 0.8 is a coefficient derived based on expert experience in the field and applicable as the in situ stresses become almost equal (hydrostatic stress) in normal faulting zones when the reservoir is depleted [86]. Conservatively, we considered 0.8 when calculating $S_{hmin}$. The pressure buildup at the end of injection is compared to the fracture pressure of the caprock using Eq. (3.1) and Eq. (3.2). If the pressure buildup is less than 80% of the fracture pressure, the sand receives the highest score and if it is 90% of the fracture pressure, the sand receives the lowest score.

The degree of faulting and presence of quaternary faults at reservoir depth were applied on the field level using 2D seismic data from GOMsmart. We could not apply the original column height and current reservoir pressure criteria because we did not have the necessary data in the datasets used for this case study. If more data is acquired in Stage 3 with this information, these criteria should be revisited during the site characterization.

### 3.2.3. Siting and economic constraints

The siting and economic constraint criteria were applied to all fields. All sites received identical scores for local public support, regulatory framework, policy support for technology, permitting, and existing $CO_2$ pipeline for our area of interest. Local public support, regulatory framework, and policy support for technology have been identified as critical barriers to widespread CCS deployment. Five emission source

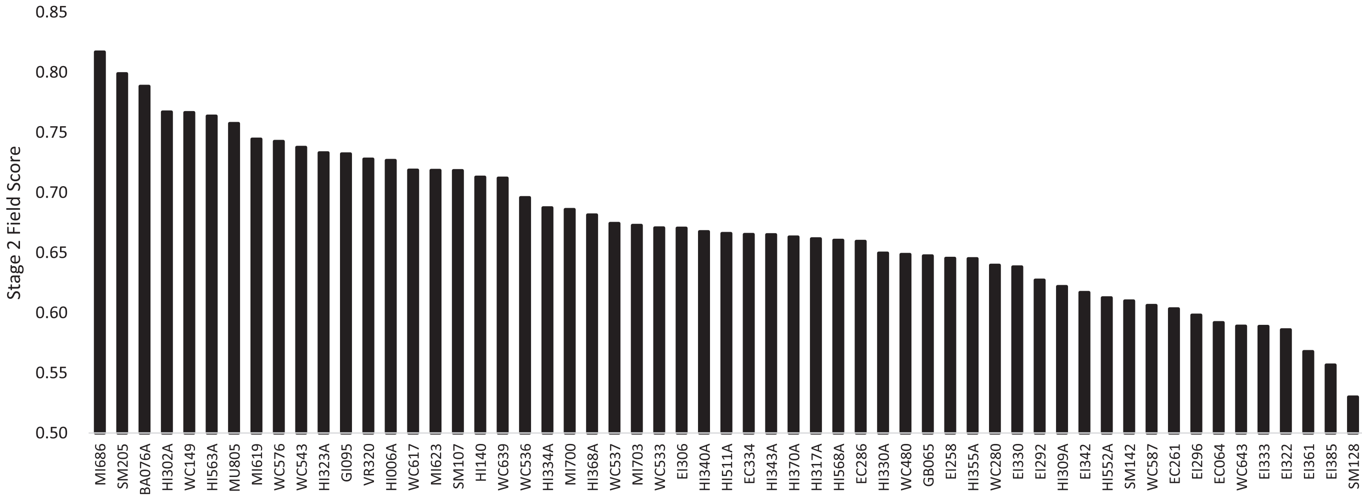


**Fig. 3.** Stage 2 total field score for 57 fields in the Gulf of Mexico. The highest-ranking field has a total score of 0.82, while the lowest ranking field has a score of 0.53.

hubs were selected along the Gulf Coast in Corpus Christi, Houston, Beaumont, Lake Charles, and New Orleans using NATCARB data [12]. All five emission source hubs have combined emissions>15 MT/yr. The distance was calculated between each site and all five source hubs, and the shortest distance was selected for each site and used to score.

#### 3.2.4. *Data confidence score*

Applying a data confidence score is one way for the user to assess the quality and quantity of data used to evaluate a site. Two data sources were used for site screening and site ranking: the BOEM dataset and GOMsmart [15,32]. GOMsmart is an online database that allows users to access oil and gas-related data for the Gulf of Mexico. Their dataset includes well tests, well logs, and seismic. For each criterion in Stage 2, the data used was given a data confidence score, either high or low (Table 3). If data is unavailable or incomplete during Stage 1 or Stage 2, the criteria that rely upon that data can be reviewed as more data becomes available in later stages. By Stage 3, data should be acquired for all criteria to characterize the reservoir. If not, a measurement campaign may be needed. In Stage 2, a data confidence score can be used to signal to the user that available data is poor or incomplete by assigning a low data confidence score. The quantity and quality of data needed for each criterion to determine if it should receive a high or low confidence score can be found in Appendix C.

#### 3.2.5. *Weighting*

Many different weighting methods are useful for multi-criteria decision-making [3,34,50,59,63;70,84]. In this case study, we assigned a relative weighting of each criterion using a paired comparison matrix (Appendix B). Each criterion is assigned a score between 1 and 3 to compare the two criteria. A score of 1 indicates that the row criterion is less important than the criterion in the column. A score of 2 indicates equal importance between the two criteria. A score of 3 indicates that the criterion in the row is more important than the criterion in the column. Each row sum is calculated. The weight assigned to each criterion is divided by the total of all the criteria scores. The capacity and injection optimization and risk minimization criteria were separated from the siting and economic constraint criteria and this exercise was performed on them separately. The sum of weights is 1 for both the technical criteria and the economic and siting criteria. The weighting factors are up to the user's discretion. The weights can be changed and adapted as the importance of specific criteria evolve.

#### 3.2.6. *Scoring*

The field score was calculated as an average of the sand score within a field. For each cluster, a capacity-weighted average of each field score was used to determine the cluster score. The results of the site ranking are found in Table 4. The highest-ranking cluster of fields is cluster 6 made up of seven fields in the West Cameron area of the Gulf of Mexico. The next highest scoring clusters are cluster 9 and cluster 8, that are made up of fields in West Cameron and High Island. The scores for the fields in Table 4 have a small spread. However, we also tested the Stage 2 scoring on a wider set of fields in the Gulf of Mexico (Fig. 3). We found that field scores ranged from a high score of 0.82 to a low score of 0.53. This distribution of scores allows for differentiation among potential sites. Fig. 4 examines the make-up of those field scores in more detail for 20 of the fields. The shape of the spider diagrams illustrates the variety of strengths and weaknesses for individual fields. Fields in close proximity such as EI330, EI292, EI333, and SM128 have similar shaped diagrams, all scoring high in depth of top of formation, permeability, porosity, stacked reservoir/seal pairs, age of existing/abandoned wells, $CO_2$ density and maximum pressure resulting on caprock. Although this is not always the case as evidenced by WC617 and WC587, which have some similar criterion scores, but not all. The shape of these diagrams shows that most of these fields have higher scores in capacity and injection optimization criteria such as depth of top of formation, porosity and permeability and generally lower scores in risk minimization criteria associated with faulting, such as degree of faulting, trap style, presence of quaternary faults at reservoir depth, and compartmentalization. Therefore, in Stage 3, a detailed reservoir characterization should examine nearby faults for potential leakage pathways as well as possible slippage.

### 3.3. *Stage 3, site characterization*

The objective of this stage is to characterize the highest-ranking sites from Stage 2. The criteria for Stage 3 are found in Table 5. For each criterion in Table 5, a narrative discusses the considerations that should be considered in Stage 3. The objective of this process is to characterize each of the top-ranking sites and determine the best site for a $CO_2$ storage project. Criteria that may have been skipped in previous stages or that had poor data quality or quantity should be reconsidered during site characterization. More data and test samples might be acquired in this stage and more certainty added.

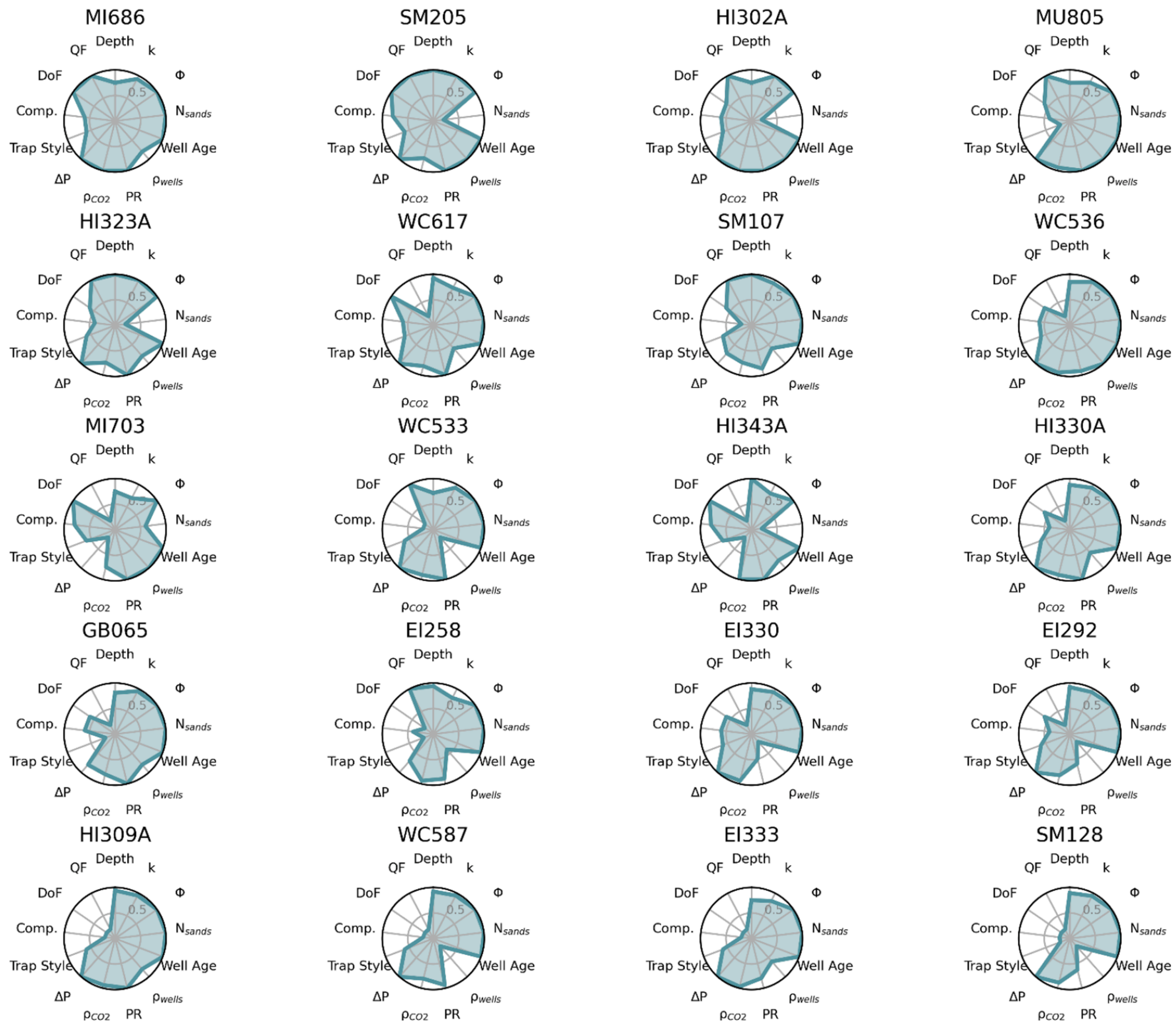


**Fig. 4.** Stage 2 field spider diagrams for a representative set of fields in the Gulf of Mexico organized from highest to lowest total field score. Abbreviations on the diagram refer to these criteria: Depth is depth of top of formation, $k$ is permeability, $\phi$ is porosity, $N_{sands}$ is stacked reservoir/seal pairs, Well Age is age of existing/abandoned wells, $\rho_{wells}$ is density of existing/abandoned wells, $PR$ is previous resource, $\rho_{CO2}$ is $CO_2$ density, $\Delta P$ is maximum plume pressure resulting on caprock, *Comp.* is compartmentalization, *DoF* is degree of faulting and *QF* is presence of quaternary faults at reservoir depth.

## 4. Discussion

The methodology presented in this work is useful to identify a field or cluster of fields for carbon storage as is illustrated by the case study in the Gulf of Mexico to find a 200MT hub-scale storage site. The workflow developed in this study builds off similar previous studies in particular the use of multiple stages and multiple criteria that address priority objectives to screen and rank potential storage locations [3,7,59,62–63;70,84]. [70] examines the benefits of using hubs and clusters for CCS deployment in hydrocarbon limited countries. To be distinguished from previous studies, the novelty of this work comes from the general applicability to all types of regions and projects, the systematic screening and ranking methodology, as well as the breadth and depth of the criteria. Specifically, the large number of potential storage sites in the Gulf of Mexico demonstrates the advantage of using the multi-stage and multi-criteria methodology. The criteria utilized in this study were developed based off a combination of expert knowledge, literature studies, and existing carbon storage projects. The site screening and ranking workflow can suit different project needs by adjusting the values assigned to the criteria. For some criteria, in particular distance from recently active faults or protected or sensitive habitats, the disqualifying threshold or scoring values were selected conservatively to avoid potential seismic risk as well as social and environmental conflict. Given the early stage of CCS deployment, the

**Table 5**
Stage 3 site characterization criteria.

| Category | Criteria | Narrative |
|---|---|---|
| Capacity and Injection Optimization | Number of Injection Wells Needed | The cost of the project increases with the number of wells that are needed for injection. However, there is an upper limit to how much can be injected into a single well. Frictional losses can be significant when injecting large volumes. There would be project risk if the project were to lose a well, injecting a large volume of $CO_2$, which could delay the project. All these factors should be evaluated when considering the number of injection wells. |
| | Vertical Heterogeneity | Vertical heterogeneity can increase the storage utilization of the reservoir. |
| | Horizontal Heterogeneity | Horizontal stratigraphic heterogeneities would guide the flow in a non-uniform areal distribution. |
| Retention and Geomechanical Risk Minimization | Top Seal Continuity | The top seal needs to be continuous over the spatial extent of the plume to minimize the chance of migration to shallower intervals or to the Earth surface. |
| | State of Stress in Top Seal | A clay-rich ductile formation is highly preferred. Low-stress anisotropy reduces the tendency for faulting and increases the hydraulic fracturing pressure. |
| | Quality of Bottom Seal | A bottom seal with permeability lower than 100nD is preferred. This will diminish the potential fluid migration pathway to the basement. |
| | Quality of Existing/ Abandoned wells | The wells in the vicinity of the $CO_2$ storage site should have passed mechanical integrity tests, have wellbore and cement evaluation logs indicating no leakage pathways through the wells, or received approval from the regulatory bodies for an alternative demonstration that the well(s) will not be a potential $CO_2$ leakage pathway. |
| | Top Seal Capillary Entry Pressure | The top seal capillary entry pressure should be great enough to prevent $CO_2$ migration through that top seal. Account should be taken of the potential for non-0° $CO_2$ -brine contact angles with adjustments made to the minimum acceptable mercury injection capillary pressure as needed. |
| | $CO_2$ Secondary Trapping Mechanisms | Solubility, residual, and mineral trapping can make the $CO_2$ immobile and increases storage security. Each trapping mechanism takes progressively longer to occur, and the amount of $CO_2$ trapped should be analyzed by numerical simulation. |
| | Pressure Buildup | Pressure change cannot exceed the hydraulic fracture pressure of the reservoir or the top seal nor increase the buoyancy pressure, so it exceeds the capillary entry pressure of the top seal. |
| | In Situ Pressure (confined reservoirs) | Strongly pressure depleted reservoirs may negatively impact a wide array of chemical and geomechanical processes relevant to both storage optimization and retention risk. |
| | Age of Fault Displacement | Determination of the age of the most recent fault displacement can show whether a fault is potentially active. |
| | Potentially Active Small-Scale Faults | If high-resolution geophysical data reveal the presence of potentially active faults, pressure changes should not exceed that which would be expected to induce slip on those faults. |

success of early projects is essential to the widespread deployment of CCS. As more projects are developed and experience gained, criteria will be modified to reflect learnings from those projects. Results are also sensitive to the weightings chosen by the user during site ranking. While these weightings can reflect the user's experience as well as the most influential criteria for a particular project or region, they can also be updated to integrate experience gained as more CCS projects are developed.

The quality and quantity of the data used to assess potential storage sites in this workflow influences the results. The outcome of this analysis is impacted if poor or insufficient data is used to evaluate sites. While using databases or atlases may be sufficient in the site screening and ranking stages, acquiring detailed data (e.g., well logs, 2D and 3D seismic, core samples) in the site characterization stage is important to verify criteria from previous stages as well as to produce more accurate assessment of the top-ranking sites before the optimal site is chosen. Future work will involve assessing and integrating a data confidence score rather than a binary high or low categorization. A data confidence score will be helpful during the transition from Stage 2 to Stage 3 where data confidence may be an influential factor in the selection of the Stage 3 site, all other factors being equal.

The results of this analysis are also sensitive to the capacity estimates. From previous studies, we know that accurate capacity estimations for carbon storage are still a major outstanding question both for storage in saline aquifers and depleted reservoirs [3,5,9,13,24;41,61,68]. The storage capacity of the site or cluster of sites is a disqualifying threshold in Stage 1 and if the estimate is inaccurate, sites may be eliminated that are large enough for the project or be kept that are not sufficient. More analysis to improve these estimates and incorporate uncertainty can be done in future work.

## 5. Conclusions

The identification of a large-number of suitable carbon storage sites is integral for the widespread deployment of CCS. The multi-criteria workflow presented in this study utilized three stages to screen, rank, and characterize potential sites based on the site capacity, injectivity, geomechanical and retention risk, as well as siting and economic constraints, ensuring all factors that influence the success of a storage project are reflected. This framework applies to various geological and geographical environments and is adaptable to project-specific constraints. The evaluation methodology draws on previous studies, expert opinion, and data compilation and availability. However, as more experience and knowledge are gained, the criteria and weightings will continue to evolve.

This framework was applied to over 13,380 sands in federal waters in the Gulf of Mexico and identified 10 suitable clusters made up of 31 fields. From the site scoring and ranking, one cluster made up of seven high-scoring fields was identified to perform a detailed reservoir characterization. The site screening criteria that removed the largest number of potential sites were the minimum thickness, water depth, and the minimum capacity needed for this hub scale project. The ten clusters that advanced to site ranking were all located near the edge of the continental shelf further offshore. With this study, we hope to introduce consistency in evaluation for future geological CCS projects that utilize depleted oil and gas reservoirs, thus improving recognition of site suitability and enhancing decision making.

*CRediT authorship contribution statement*

**Catherine Callas:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Sarah D. Saltzer:** Methodology, Writing – original draft, Writing – review & editing, Funding acquisition. **J. Steve Davis:** Methodology, Writing – original draft, Writing – review & editing. **Sam S. Hashemi:** Methodology, Writing – original draft, Writing – review & editing. **Anthony R. Kovscek:** Supervision, Writing – review & editing. **Esuru R. Okoroafor:** Writing – original draft, Writing – review & editing. **Gege Wen:** Writing – review & editing. **Mark D. Zoback:** Conceptualization, Supervision. **Sally M. Benson:** Conceptualization, Methodology, Supervision, Funding acquisition.

## 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. . Calculation of maximum pressure buildup on caprock

See Table A1.

The number of injection wells was calculated by Eq. (A1):

$$Number\ of\ Injection\ Wells = \frac{10\,MT\,CO_2 * w_i}{11,000\ \frac{tonnes\ of\ CO_2}{m} * b_i} \tag{A1}$$

$$where w_i = \frac{b_i}{\sum_{i=1}^{N_{tot}} b_i}$$

$w_i$ is the weighting of each sand and $b_i$ is the sand thickness as provided by the BOEM dataset.

The pressure buildup from multiple wells was calculated using the principle of superposition (Eq. (A2)):

$$\Delta p(r_w, t)_{well\ 1} = \Delta p(r_w, t)_{well\ 1} + \Delta p(r_w, t)_{well\ 2} \tag{A2}$$

**Table A1**
The parameters used to calculate the maximum pressure buildup.

| Parameter | Value | Source |
|---|---|---|
| Permeability (k) | Given by sand (mD) | [15] |
| Thickness (h) | Given by sand (m) | [15] |
| Porosity ($\phi$) | Given by sand | [15] |
| Injection Rate per m per year per well | 11,000 tonnes/m | [33] |
| Water Viscosity ($\mu_w$) | $2.414*10^{-5} Pa \bullet s*10^{\frac{247.8}{T(K) - 140K}}$ | [27] |
| Compressibility ($c_t$) | $10^{-8}$ 1/kPa | [53] |
| Radius (r) | 0.1 $m$ | |
| Total Mass of $CO_2$ Injected into Field per year | 10 MT/yr | |
| Time (t) | 20 years | |

## Appendix B. . Weighting matrix used for Gulf of Mexico case study

See Tables B1 & B2.

**Table B1**
Technical score paired comparison weighting matrix. A one means the row criterion is less important than the column criterion. A two means both criteria are equally important and a three means the row criterion is more important than the column criteria.

| Horizontal Controls: (2 equal, 1 worse, 3 better) | Compartm entalization | Depth of Top of Formation | Permea bility | Porosity | Buoyancy Pressure Difference | Stacked Reservoi r/Seal Pairs | Trap Style | Degree of Faulting | Presence of Quaternary Faults at Reservoir Depth | Density of Existing /Abandoned Wells | Age of Existing/ Abandon ed Wells | Previous Resource in Reservoir | Max Plume Pressure resulting on Caprock | Reservo ir Current Pressure | $CO_2$ Density |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Compartmentalization | | 3 | 1 | 1 | 3 | 3 | 3 | 2 | 1 | 1 | 2 | 3 | 2 | 1 | 3 |
| Depth of Top of Formation | 1 | | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 |
| Permeability | 3 | 3 | | 3 | 3 | 3 | 3 | 2 | 1 | 2 | 3 | 3 | 3 | 2 | 3 |
| Porosity | 3 | 3 | 1 | | 3 | 3 | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Buoyancy Pressure Difference | 1 | 3 | 1 | 1 | | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 |
| Stacked Reservoir/ Seal Pairs | 1 | 2 | 1 | 1 | 2 | | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Trap Style | 1 | 3 | 1 | 1 | 2 | 2 | | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Degree of Faulting | 2 | 3 | 2 | 3 | 3 | 3 | 3 | | 1 | 2 | 2 | 3 | 3 | 3 | 3 |
| Presence of Quaternary Faults at Reservoir Depth | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | | 2 | 2 | 3 | 3 | 3 | 3 |
| Density of Existing/ Abandoned Wells | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 2 | 2 | | 2 | 3 | 3 | 3 | 3 |
| Age of Existing/ Abandoned Wells | 2 | 3 | 1 | 3 | 3 | 3 | 3 | 2 | 2 | 2 | | 3 | 3 | 3 | 3 |
| Previous Resource in Reservoir | 1 | 3 | 1 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 | | 1 | 1 | 3 |
| Max Plume Pressure resulting on Caprock | 2 | 3 | 1 | 3 | 2 | 3 | 3 | 1 | 1 | 1 | 1 | 3 | | 1 | 3 |
| Reservoir Current Pressure | 3 | 3 | 2 | 3 | 3 | 3 | 3 | 1 | 1 | 1 | 1 | 3 | 3 | | 3 |
| $CO_2$ Density | 1 | 2 | 1 | 3 | 2 | 3 | 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | |

**Table B2**
Siting and economic constraints paired comparison weighting matrix. A one means the row criterion is less important than the column criterion. A two means both criteria are equally important and a three means the row criterion is more important than the column criteria.

| Horizontal Controls: (2 equal, 1 worse, 3 better) | Local Public Support | Regulatory Framework | Policy Support for Technology | Economies of Scale associated with $CO_2$ Source | Proximity to Sources | Permitting | Existing $CO_2$ Pipeline |
|---|---|---|---|---|---|---|---|
| Local Public Support | | 1 | 1 | 3 | 3 | 2 | 1 |
| Regulatory Framework | 3 | | 3 | 3 | 3 | 3 | 2 |
| Policy Support for Technology | 3 | 1 | | 3 | 3 | 2 | 2 |
| Economies of Scale associated with $CO_2$ Source | 1 | 1 | 1 | | 2 | 1 | 2 |
| Proximity to Sources | 1 | 1 | 1 | 2 | | 2 | 1 |
| Permitting | 2 | 1 | 2 | 3 | 2 | | 2 |
| Existing $CO_2$ Pipeline | 3 | 2 | 2 | 2 | 3 | 2 | |

## Appendix C. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2022.119668.

## References


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