Estimating Carbon Storage Resources in Offshore Geologic Environments

14 August 2018
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Cover Illustration: Sedimentary basins in North America with outlined offshore U.S. waters.


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https://edx.netl.doe.gov/carbonstorage
Estimating Carbon Storage Resources in Offshore Geologic Environments

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# Table of Contents

EXECUTIVE SUMMARY ...........................................................................................................1  
1. BACKGROUND ..................................................................................................................2  
2. MOTIVATION FOR OFFSHORE CARBON STORAGE .....................................................3  
3. CARBON STORAGE RESOURCE ASSESSMENTS..............................................................4  
  3.1 CARBON STORAGE ASSESSMENT APPROACHES......................................................4  
  3.2 DEFINING GEOLOGICAL SETTINGS FOR CARBON STORAGE .................................5  
  3.3 DOE METHODOLOGY FOR CARBON STORAGE ESTIMATES.......................................5  
  3.4 CO₂-SCREEN TOOL FOR SALINE STORAGE ASSESSMENTS....................................8  
4. PARAMETERS UNIQUE TO OFFSHORE SUBSURFACE STORAGE...................................9  
  4.1 PRESSURE-TEMPERATURE (P-T) CONDITIONS ........................................................9  
  4.2 GEOMECHANICAL AND ROCK PROPERTY CONSIDERATIONS .............................11  
  4.3 DISSOLVED CO₂-BRINE INTERACTIONS ....................................................................13  
  4.4 ECONOMIC, ENVIRONMENTAL, AND LOGISTICAL CONSIDERATIONS .........13  
5. DISCUSSION OF AN OFFSHORE METHODOLOGY ..................................................15  
6. FUTURE WORK .................................................................................................................18  
  6.1 APPLYING ONSHORE CALCULATIONS TO ESTIMATE OFFSHORE CO₂ STORAGE EFFICIENCY AND CAPACITY ..........................................................18  
  6.2 GEOSPATIAL ANALYSIS FOR OFFSHORE STORAGE PROSPECTS ......................18  
  6.3 MODIFYING EFFICIENCY FACTORS FOR OFFSHORE STORAGE ..........................19  
7. SUMMARY ........................................................................................................................20  
8. REFERENCES.......................................................................................................................21
List of Figures

Figure 1: Approximate phase diagram displaying the pressure (bars) and temperature (degrees Celsius) conditions with depth (kilometers) when drilling: A. (blue) onshore at sea level (0 km), B. (red) offshore at a depth of 500 m, and C. (green) offshore at a depth of 4 km. The upper half of the figure illustrates simplified drilling paths A, B, and C; and the lower half of the figure illustrates the pressure-temperature conditions along each path. The P-T conditions at the seafloor are illustrated with the brown line. Hydrostatic pressures are assumed in sediments along with a geothermal gradient of 25 degrees Celsius/km. The CO$_2$ hydrate phase field is from Sloan (1990). ............................................................................... 6

Figure 2: The CO$_2$ negative buoyancy zone near the sediment-water interface at 3,500 m water depth. Using the same drilling paths from Figure 1, the blue, red, and green lines show the density of CO$_2$ onshore (calculated) and offshore (House et al., 2006). In purple is the calculated CO$_2$ density near the SWI. The orange is seawater density, based on the National Institute of Standards and Technology (NIST) Webbook (Lemmon et al., 2011). ............... 10
## Acronyms and Abbreviations

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-D</td>
<td>Three-dimensional</td>
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<tr>
<td>4-D</td>
<td>Four-dimensional</td>
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<tr>
<td>BOEM</td>
<td>Bureau of Ocean Energy Management</td>
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<tr>
<td>CCS</td>
<td>Carbon capture and storage</td>
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<td>CO₂</td>
<td>Carbon dioxide</td>
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<tr>
<td>CO₂-SCREEN</td>
<td>CO₂ Storage prospeCtive Resource Estimation Excel aNalysis</td>
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<tr>
<td>CSIL</td>
<td>Cumulative Spatial Impact Layers</td>
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<td>CSLF</td>
<td>Carbon Storage Leadership Forum</td>
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<tr>
<td>EERC</td>
<td>Energy and Environmental Research Center</td>
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<tr>
<td>EOR</td>
<td>Enhanced oil recovery</td>
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<tr>
<td>EPA</td>
<td>U.S. Environmental Protection Agency</td>
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<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
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<tr>
<td>IEAGHG</td>
<td>International Energy Agency Greenhouse Gas R&amp;D Program</td>
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<tr>
<td>NETL</td>
<td>National Energy Technology Laboratory</td>
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<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
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<td>OGIP</td>
<td>Original gas in place</td>
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<td>OOIP</td>
<td>Original oil in place</td>
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<tr>
<td>P-T</td>
<td>Pressure-temperature</td>
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<td>RCSP</td>
<td>Regional Carbon Sequestration Partnership</td>
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<td>STA</td>
<td>Subsurface Trend Analysis</td>
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<td>SWI</td>
<td>Sediment-water interface</td>
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<td>SWIM</td>
<td>Spatially Weighted Impact Model</td>
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<td>TDS</td>
<td>Total dissolved solids</td>
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<td>VGM</td>
<td>Variable Grid Method</td>
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Acknowledgments

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EXECUTIVE SUMMARY

Long-term carbon storage in geologic reservoirs is a leading technique for removing excess carbon dioxide (CO₂) that would otherwise be emitted to the atmosphere as a result of anthropogenic activities. Effective carbon storage requires both safety and permanence. One underutilized national storage scenario involves carbon storage in offshore geologic formations, similar to those that hold oil, gas, or brine. This scenario has been tested in other countries on a small-scale, but is yet unproven in the United States. A major advantage of offshore storage is that the risk of carbon dioxide leakage into fresh groundwater resources is decreased, and the effect of that leakage on human population centers is minimized. However, as with onshore storage scenarios, there are many uncertainties surrounding offshore storage. These include issues related to both safety and permanence. After an extensive literature review of the current storage methodologies for onshore carbon storage in saline formations, comparing and contrasting the offshore and onshore characteristics of reservoirs, this study makes recommendations about future work to support offshore storage estimates and research. This report concludes with the suggestion that despite important differences between onshore and offshore systems, carbon can be stored safely and permanently in offshore saline geologic formations. This research proposes using the U.S. Department of Energy’s (DOE), National Energy Technology Laboratory (NETL) saline storage methodology with an integration of spatial-statistical tools to adjust for uncertainties.
1. BACKGROUND

Carbon capture and storage (CCS) technologies rely on dependable carbon storage estimates (Bachu, 2000; Bachu et al., 2007; USGS, 2013; Goodman et al., 2011), and governments and businesses worldwide depend on these estimates for policy and decision-making. An effort by the U.S. Department of Energy (DOE) in 2013 summarized six existing methodologies for estimating carbon storage potential for saline formations developed by various groups, resulting in a recommended DOE carbon storage methodology (Goodman et al., 2013). Most of the current initiatives focus on onshore storage scenarios for a variety of reasons, typically proximity to CO2 sources but also greater certainty about onshore geologic formation properties. This study presents the findings regarding if storage was to be explored offshore, and if the DOE recommended carbon storage methodology could be used for offshore storage estimates “as is” or would have to be modified. This report explores some of the findings from an extensive literature review, explains why the DOE carbon storage methodology should work for offshore storage sites (with a few caveats), and finally, suggests the next tasks in developing estimates of offshore carbon storage potential. In general, this methodology applies to offshore saline storage and is not limited to storage in oil bearing reservoirs.
2. **MOTIVATION FOR OFFSHORE CARBON STORAGE**

CCS technologies rely on dependable carbon storage estimates (Bachu, 2000; Bachu et al., 2007; USGS, 2013; Goodman et al., 2011), and governments and businesses worldwide depend on these estimates for policy and decision-making. An effort by the DOE in 2013 summarized the top six existing methodologies for estimating carbon storage potential developed by various groups, resulting in a recommended DOE carbon storage methodology (Goodman et al., 2013). Most carbon capture and storage estimates focus on onshore scenarios for capturing carbon and/or storage. This is because large, stationary emission sources (e.g., factories, power plants, concrete plants, etc.) are easier to identify than offshore sources (NETL, 2015). There are 6,358 stationary CO₂ sources in the onshore and offshore U.S. and Canada documented in the Carbon Storage Atlas V (2015). Most studies have considered storage near a point source, which are predominantly onshore facilities, to decrease costs associated with transportation. However, there are a number of nearshore and shallow offshore greenhouse gas (GHG)-generating facilities for which pipeline distances could be minimized. Offshore storage decreases risks to population centers and leakage risks associated with groundwater resources. Additionally, there are a number of regions within the U.S. that lack suitable onshore storage options or options that may be unfeasible for other reasons.

This report addresses the following questions: What is different about offshore subsurface saline formation storage that might have to be taken into account when calculating storage resource estimates? How can the DOE recommended carbon storage methodology be adapted to estimate offshore saline carbon storage resources? This report further recommends ways that the DOE carbon storage methodology should be implemented for determining offshore storage capacity, and suggests additional work to improve offshore carbon storage estimates relying on NETL geospatial toolsets.
3. CARBON STORAGE RESOURCE ASSESSMENTS

3.1 CARBON STORAGE ASSESSMENT APPROACHES

As a foundation for generating an offshore storage assessment methodology, the first step was to establish what other types of storage assessment methodologies existed, both on and offshore, via an extensive literature review. World-wide, numerous countries aside from the United States have conducted regional carbon storage assessments. In Europe, 23 countries were assessed by the European Union GeoCapacity project (Donda et al., 2011; Hatziyannis et al., 2009; Le Nindre et al., 2011; Martinez et al., 2009; Radoslaw et al., 2009; Vangkilde-Pedersen et al., 2009a; Vangkilde-Pedersen et al., 2009b) and the Norwegian Petroleum Directorate (Halland et al., 2014). Assessments were also done for Australia (Bradshaw et al., 2011), Brazil (Ketzer et al., 2015), South Africa (Cloete, 2010), and Japan (Ogawa et al., 2011; Takahashi et al., 2009; NETL, 2016a). Many of these assessments have used a methodology described by the Carbon Storage Leadership Forum (CSLF) (Bachu et al., 2007), which uses volumetric equations similar to those described by the DOE methodology (Goodman et al., 2011, 2013). Comparisons of several volumetric methodologies for estimating storage in saline formations, including the CSLF and DOE methodologies, have found differences to be statistically insignificant (Goodman et al., 2013).

A storage resource assessment can be based on a simple volumetric equation based on geologic parameters such as those mentioned previously, but can also be enhanced by using ranking systems or including economics and other factors. These additional factors are incorporated into assessments conducted by Norway (Halland et al., 2014), Australia (Bradshaw et al., 2011; Spencer et al., 2011), Brazil (Ketzer et al., 2015), China (Jian, 2014), and Japan (Ogawa et al., 2011; Takahashi et al., 2009). Specifically, these assessments detail each country’s classification or ranking system used to determine the favorability of the prospective basin or reservoir-seal pair of interest and also address regulatory and economic restrictions. The CSLF 2015 report on offshore sub-seabed geologic storage of CO₂ recommends a more comprehensive assessment methodology that defines an area based on a known trap, then uses constraints such as distance from a CO₂ source, tectonic environment, faults, geothermal and hydrothermal properties, reservoir and seal favorability, and socio-economic factors, as appropriate, to define the area assessed for storage (Offshore Storage Technologies Task Force, 2015). This is more detailed and comprehensive than simple volumetric storage assessments.

In the U.S., most assessments have focused on onshore regions because of proximity to point sources. The Carbon Storage Atlas V (NETL, 2015) uses a broad volumetric calculation to estimate carbon storage resources for the whole U.S., based on inputs provided by the Regional Carbon Sequestration Partnership (RCSP). However, regional and sub-regional offshore carbon storage assessments are underway. The Gulf of Mexico Miocene CO₂ Site Characterization Mega-Transect project conducted a detailed sub-regional assessment of the nearshore Texas coast (Meckel and Trevino, 2014). The study characterized the Miocene-age sediments in a defined region along the Texas coast, with storage estimates developed using both regional static calculations and site-scale dynamic models in select locations. Multiple data types and sources, including well logs, core analyses, and seismic data, were used to map and characterize the geology of the potential reservoirs. Detailed site characterization, including dynamic modeling, was conducted for several sites, and pressure was found to be the “major limiting parameter.”
They also indicate that reservoir heterogeneity was found to be an important obstacle to the assumption of an open system.

The DOE methodologies provide the basis for the offshore methodology proposed later in this paper. However, insights gained from other more comprehensive studies, like those mentioned above, were utilized in the recommendations that follow for addressing offshore-specific geological, environmental, and logistical storage assessment considerations.

3.2 DEFINING GEOLOGICAL SETTINGS FOR CARBON STORAGE

Carbon storage assessment methodologies vary depending on the geologic setting. Most simply, these methodologies can be split into assessing either conventional or unconventional storage formations. Conventional geologic formations of interest for carbon storage include porous and permeable sedimentary rocks in deep saline formations, or depleted oil and gas fields with known storage capacity (Goodman et al., 2011). Conventional settings predominantly rely on structural trapping. Offshore porous sedimentary formations with conventional seals are the focus of the offshore DOE methodology.

Unconventional settings being explored for carbon storage include gas shales, unmineable coal seams, basalt formations, or gravitational trapping in deep ocean sediment systems (Levine et al., 2007). These proposed unconventional storage strategies take advantage of the subsurface pressure-temperature conditions and geology of offshore systems, and utilize the other methods of CO2 trapping. For example, carbon storage via injection into seafloor basalts (Goldberg et al., 2008; Goldberg and Slagle, 2009; Marieni et al., 2013) assumes the injected CO2 can permanently react with basic igneous oceanic crust. Another proposed strategy is to store CO2 in near-mudline sediments below a deep water column (Levine, et al., 2007). This technique depends on the high pressures and low temperatures of the deep ocean margin resulting in non-buoyant CO2 phases either below low permeability sedimentary seals or below self-generated seals such as hydrate phases (e.g. House et al., 2006; Schrag et al., 2009; Qanbari et al., 2012; Levine et al., 2007). Unconventional storage formations offshore deserve a mention as potentially viable pending future work, but are not the focus of the rest of this paper.

3.3 DOE METHODOLOGY FOR CARBON STORAGE ESTIMATES

Based on the findings from an extensive literature review of assessment methodologies from other countries, the recommendation going forward is to continue using the DOE methodology for carbon storage resource estimates and taking a few extra factors discussed in section 4 into consideration. The DOE methodology is simple and straightforward without being unnecessarily cumbersome. As Goodman et al. (2016) points out, there is a major distinction between a method and a methodology. “A methodology is a body of methods, rules and conceptual modes of thinking that provide the theoretical basis underlying an analysis. By comparison, a method is a particular application of a methodology, with a specific and defined algorithm for computing a particular number.” This section reviews the two DOE equations used to calculate the volume available for subsurface storage. These are discussed in further detail in Goodman et al. (2011) and Goodman et al. (2016).
3.3.1 Estimating Carbon Storage in Conventional Saline Formations

In order to generate national and regional carbon storage assessments, the DOE developed methodologies for estimation of carbon storage resources in deep, saline formations and depleted oil and gas reservoirs. A formation of interest must meet several criteria, including:

1) Pressure and temperature conditions sufficient to store CO$_2$ in a dense fluid state (Figure 1) which generally occurs at depth greater than 800 m hydrostatic pressure (Goodman et al., 2011; NETL, 2015)

2) Formation water is not potable, where potable ground water is defined as having less than 10,000 parts per million (ppm) total dissolved solids (TDS) by the U.S. Environmental Protection Agency’s Safe Drinking Water Act (EPA, 2010)

3) A formation seal (or caprock) is present

![Figure 1: Approximate phase diagram displaying the pressure (bars) and temperature (degrees Celsius) conditions with depth (kilometers) when drilling: A. (blue) onshore at sea level (0 km), B. (red) offshore at a depth of 500 m, and C. (green) offshore at a depth of 4 km. The upper half of the figure illustrates simplified drilling paths A, B, and C; and the lower half of the figure illustrates the pressure-temperature conditions along each path. The P-T conditions at the seafloor are illustrated with the brown line. Hydrostatic pressures are assumed in sediments along with a geothermal gradient of 25 degrees Celsius/km. The CO$_2$ hydrate phase field is from Sloan (1990).](image)
The DOE saline methodology only considers physical trapping of free phase CO\textsubscript{2}. The phases of CO\textsubscript{2} trapped by other methods, such as dissolution trapping or mineral carbonation, while substantial, are neglected for simplicity. It is also assumed that the formation will effectively behave as an open system, where in situ formation fluids are displaced by the injected CO\textsubscript{2} without causing significant pressure increase, or that the fluids will be pressure-managed during injection (Goodman et al., 2011). A note: the DOE methodologies for resource estimates consider only physical storage space accessible to CO\textsubscript{2}; they do not currently incorporate economic, regulatory, or logistical constraints (NETL, 2015).

The refined DOE methodology for saline formations to estimate \( G \), the mass of CO\textsubscript{2} that can be stored, is estimated using the following volumetric-based equation:

\[
G_{\text{CO}_2} = A_t h_g \phi_{\text{tot}} \rho E_{\text{saline}}
\]  

The parameters to determine \( G \) are: total area (\( A_t \)) of the formation of interest, gross thickness (\( h_g \)) of the formation, and total porosity of that formation (\( \phi_{\text{tot}} \)), representing the bulk volume of pore space in the formation. The density of CO\textsubscript{2} at formation pressure and temperature is \( \rho \). The percentage of the bulk volume accessible to CO\textsubscript{2} (Goodman et al., 2011) is represented by the efficiency factor \( E_{\text{saline}} \), which comprises five terms:

\[
E_{\text{saline}} = E_A * E_h * E_{\phi} * E_v * E_d
\]

The saline efficiency factors are: \( E_A \), the ratio of net-to-total area, \( E_h \), the net-to-gross thickness, \( E_{\phi} \), the effective-to-total porosity, \( E_v \), a volumetric displacement efficiency factor, and \( E_d \), the microscopic displacement efficiency factor. Values for the E terms have been estimated by Monte Carlo sampling of data from world-wide hydrocarbon reservoirs. Less comprehensive saline formation data is available, so data from petroleum fields are used as an analogue (International Energy Agency Greenhouse Gas R&D Program, IEAGHG, 2009).

### 3.3.2 Estimating Carbon Storage in Depleted Petroleum Fields

The other DOE methodology for estimation of storage resource volume in depleted oil and gas reservoirs can be estimated using either the actual production volumes, if known, or a volumetric equation. If production values are available, they can be converted to estimated carbon storage by applying a reservoir volume factor, as well as an efficiency factor, if information on efficiency is available. If production information is not known, the volumetric equation to estimate carbon storage resources is:

\[
G_{\text{CO}_2} = A h_n \phi_e (1 - S_{\text{wi}}) B \rho_{\text{CO}_2\text{std}} E_{\text{oil}}
\]

The following terms together describe the original oil in place (OOIP) or original gas in place (OGIP): area (\( A \)), net thickness (\( h_n \)), effective porosity (\( \phi_e \)), original hydrocarbon saturation (\( 1 - \) water saturation \( S_{\text{wi}} \), and the hydrocarbon formation volume factor at bubblepoint pressure (\( B \)). The terms to adjust for CO\textsubscript{2} are: \( \rho_{\text{CO}_2\text{std}} \), the density of CO\textsubscript{2} at standard pressure and
temperature, used to convert volume to mass, and \(E_{\text{oil/gas}}\), an efficiency factor describing the percentage of the bulk volume accessible to CO\(_2\) (Goodman et al., 2011).

### 3.4 CO\(_2\)-SCREEN TOOL FOR SALINE STORAGE ASSESSMENTS

Researchers at NETL have developed a tool that allows the saline storage methodology to be applied using a probabilistic model (Goodman et al., 2016). NETL’s CO\(_2\)-SCREEN tool is designed to aid investigators in screening onshore basins and formations for prospective carbon storage resources (Sanguinito et al., 2017). It provides a method for a quick prospectivity analysis and can also be used to refine initial storage estimates as new data is collected. The tool also allows researchers to screen basins and formations for rough estimates of storage resource potential. No spatial or structural uncertainty is incorporated into the model. The tool is a Microsoft Excel-based platform for inputting geologic model parameters followed by a Monte-Carlo simulation according to those geological inputs. The inputs may be entered two ways, either manually based on actual data or on an analogue dataset, or auto-populated based on three pre-set lithologies and ten depositional environments that are provided with the tool. See Sanguinito et al. (2017) for a more in-depth explanation of how to use the CO\(_2\)-SCREEN tool.
4. PARAMETERS UNIQUE TO OFFSHORE SUBSURFACE STORAGE

Although it is easy to visually identify the transition between land and sea, the sedimentological transition between onshore and offshore is more difficult to define. This transition cannot be extrapolated directly down from the present-day shoreline. Marine sediments may be found onshore, just as fluvial deposits are common in shallow shelves offshore. The pressure from the water column and the effect of saturated sediments on the lithification process are enough to consider a distinct offshore storage methodology. This study assumes that “offshore” basins are under water, are currently accumulating sediments and are generating overpressure, whereas “onshore” basins are erosional but could also be subject to pressure issues. Sediment characteristics between offshore and onshore depositional environments are varied. Finally, the water column itself impacts temperature and pressure in the subsurface environment.

4.1 PRESSURE-TEMPERATURE (P-T) CONDITIONS

Most carbon storage scenarios assume CO₂ will be stored as a dense supercritical fluid to maximize storage and transport efficiency. The reservoir pressure and temperature conditions are primary factors in evaluating a prospective reservoir. In order for the CO₂ to remain in a dense state, the storage formation must be at a combination of sufficiently high pressure or low temperature. Density increases with increasing pressure, but decreases with increasing temperature. The CO₂ triple point is at 7.38 MPa and 31.1°C (Figure 1). Beyond this point, CO₂ exists as a supercritical fluid which has the advantage of low fluid viscosities but high fluid densities (Bachu, 2003). For most regional CO₂ resource estimates onshore, the minimum required depth for storage conditions has been assumed to be 800 m as a rule of thumb, based on analyses of CO₂ density at hydrostatic pressure and typical geothermal gradients (Bachu, 2003; Chadwick et al., 2008; Vangkilde-Pedersen et al., 2009b).

Because dense CO₂ is typically more buoyant than formation water, storage and trapping mechanisms must prevent the upward movement of CO₂ along buoyant flow pathways. Onshore and offshore systems exhibit a similar trend of increasing pressure and temperature below the land surface or sediment-water interface (SWI). However, because of the water column over offshore sediments, the initial pressure and temperature at the SWI are primarily a function of ocean depth, with cold deepwater temperatures ~5°C coinciding with hydrostatic pressure gradients of ~ 1 bar/10 m (or 0.1 MPa/10 m). Pressure-temperature (P-T) regimes in the deep ocean can exhibit density stable (negatively-buoyant or non-buoyant phases) (Figure 2) of CO₂ such as liquid CO₂ and a variety of hydrates (House et al., 2006).
Figure 2: The CO₂ negative buoyancy zone near the sediment-water interface at 3,500 m water depth. Using the same drilling paths from Figure 1, the blue, red, and green lines show the density of CO₂ onshore (calculated) and offshore (House et al., 2006). In purple is the calculated CO₂ density near the SWI. The orange is seawater density, based on the National Institute of Standards and Technology (NIST) Webbook (Lemmon et al., 2011).

On continental shelves, the influence of the water column on both temperature and pressure may be negligible when water is shallow. As water depth increases, the temperature at the SWI decreases in concert with increasing pressure. Owing to wider variations in pressure and temperature with depth due to the shelf slope, CO₂ density should be calculated based on estimated P-T conditions prior to generating a minimum depth criteria. One tool for this is the Carnegie Mellon University Carbon Dioxide Properties Excel Add-in (McCoy, 2004). For example, Gulf of Mexico formations as shallow as 500 m subsurface may have sufficient P-T conditions for storing supercritical CO₂, but these formations may not be suitable for carbon storage for other reasons.
4.2 GEOMECHANICAL AND ROCK PROPERTY CONSIDERATIONS

An offshore storage resource assessment should also take into consideration the consolidation of the storage medium for two reasons: 1) the competency of the prospective storage formation, and 2) the competency and presence of the confining seal rock. Empirically, even relatively unconsolidated sediments in the Gulf of Mexico are prospective as a storage resource due to their known ability to hold oil or gas. Miocene and younger sediments are unconsolidated to slightly consolidated turbidite sands and mudstones (Ostermeier, 2001). These young sediments are likely targets for carbon storage due to their appropriate depth ranges (~800 m–3,000 m), sealing units, porosity and permeability values, and higher compressibility (Meckel and Trevino, 2014; Gorecki et al., 2015). Although the formation consolidation can be fairly easily dismissed, there are several other geomechanical and rock property considerations that should be discussed in further detail.

4.2.1 Reservoir Seal Presence

Once P-T conditions are satisfied for possible storage, the most critical parameter for short-term and structurally-trapped subsurface carbon storage is the presence of an effective upper and lateral seal. Without a sealing unit, the more buoyant CO₂ will rise through the subsurface, regardless of storage formation. A typical sealing formation in the sedimentary column is composed of fine-grained material forming a low permeability, continuous layer emplaced by subsequent sedimentation, faulting, or lateral depositional environmental changes. Diagenetic changes including compaction and cementation can reduce permeability of sediments, thereby enhancing seals in otherwise permeable sediments. In the shallow sub-seabed environment, the uncompacted, unconsolidated sediments limit seal potential as porosity and permeability remain high (Offshore Storage Technologies Task Force, 2015). Deeper in the sediment column, however, diagenetic processes, sealing faults, and compaction of sediments create conditions that inhibit the flow of fluids out of the system. Burial compaction reduces the porosity of clay formations from 80% at the SWI to as little as 5% (Osborne and Swarbrick, 1997) as pore fluid is expelled.

4.2.2 Seal and Storage Formation Rock Properties

This section generally refers to the young, unconsolidated sediments in a basin with adequate accommodation space for continued and rapid deposition than to sediments in a mature basin that have been compacted and lithified. Unconsolidated sediments are mechanically weaker than lithified rock, but their ductility provides certain advantages for carbon storage. For sealing units, strain in unconsolidated sediments is typically creeping strain promoted by high clay contents that induce self-sealing behavior (Offshore Storage Technologies Task Force, 2015; Meckel and Trevino, 2014; Zoback, 2010; Ostermeier, 2001; Hart et al., 1995). This has major implications on the suitability of the sealing units because ductile deformation of mudstone seals potential leakage pathways to the surface, including natural pathways such as faults, and man-made pathways such as well boreholes (Clark, 1987).

Open or active faults act as the primary leakage pathways for buoyant fluids in the subsurface and should be an important consideration for offshore carbon storage prospecting. Faults in offshore unconsolidated sediments behave aseismically (Zoback, 2010) and can act as sealing structures or conduits depending on their stress state. Overpressure from fluid expulsion increases stress on preexisting faults and if they are near their critical stress point, injecting more
fluid can cause faults to reopen and provide a path for upward fluid migration. Seeps, vents, and mud volcanoes are surface expressions of deeper upward fluid migration along various pathways. Rapid fluid or gas expulsion is often brief and episodic resulting in a valve-like process of opening and closing faults and fractures episodically relieving overpressure. While critically stressed faults can be conduits for flow, the plastic, self-healing nature of unconsolidated sediment may suggest that when not critically stressed, the faults are closed. This reduces the risk of upward fluid migration. When not critically stressed, faults will tend to close in relatively short time scales. As the pressure builds once more, the fault will then be more likely to reopen and allow fluid flow along a pressure gradient (Zoback, 2010; Wiprut and Zoback, 2000; Talukder, 2012). As a frame of reference, in onshore storage formations where fluid pressures have largely equilibrated with the surrounding pressure environment over time, the risk for pulse leakage of fluid and gas is less without tectonic forces.

Active faulting and geomechanical complications are often found in basins experiencing salt migration, basins exhibiting rapid deposition which load stratigraphy and induce growth faulting, or tectonically active margins. Some of the offshore considerations listed previously have negligible impact, such as in a sediment-starved or mature basin, whereas almost all of the geomechanical considerations listed could have an impact in a rapidly changing basin such as the Gulf of Mexico.

4.2.3 Pressure Management in the Storage Formation

Depending on depositional environment and regional structural complexity, a reservoir formation can be highly compartmentalized both vertically and laterally or can be laterally extensive. A key assumption from the DOE carbon storage methodology is that CO₂ efficiency factors are based on open systems: a reservoir is characterized as open or closed based on the ability to dissipate pressure. In closed systems, it may be difficult to reach the maximum storage potential without pressure management strategies, so CO₂ volumes will depend on the compressibility of the formation and the pore fluid. Gorecki et al. (2009) estimate carbon dioxide storage in closed systems without pressure management can be as much as 25 times less than that in open systems where brine is displaced freely.

Overpressure is common in offshore formations. The same mudrocks being deposited with 80% porosity are full of pore fluid that becomes trapped as those formations are buried. When fluid pressure in a zone exceeds that of the hydrostatic pressure gradient (~0.47 psi/ft in seawater), the zone is considered overpressured. Zones experience overpressure when impermeable layers slow or prevent expulsion of pore fluid, and continued sediment loading or other mechanisms (Osborne and Swarbrick, 1997, Hart et al., 1995) raise the fluid pressure above the hydrostatic gradient. Overpressured environments exhibit pore pressures close to or at fracture pressure, thus increasing the risk of fault reactivation or fracture initiation upon injection. Operations in storage units with a narrow pressure gradient margin or operating window must be pressure managed to reduce the risk of breaching seals, causing leakage and inducing seismic activity (Zoback and Gorelick, 2012). As a reference point, overpressure in onshore formations can happen, but is most often detected via earthquake swarms.
4.3 DISSOLVED CO₂-BRINE INTERACTIONS

Most sections in this report primarily focus on buoyant CO₂ storage in a structural trapping setting. Free CO₂ remains buoyant in subsurface reservoirs. However, it is possible for CO₂ to be dissolved into reservoir brines. In response to free phase CO₂ dissolution into the brine, the density of the brine increases, resulting in a “brine mixing” process within the storage formation. Density driven flows in the brine increase the rate of undersaturated brine interaction with a CO₂ plume (Ennis-King et al., 2003; Bachu, 2015) further enhancing dissolution. When CO₂ is stored in brine formations as dissolved CO₂ or bicarbonate, the risk of buoyant leakage is eliminated. Considering dissolved carbon storage as one end-member, the minimum long-term carbon storage potential of a reservoir is equivalent to the mass of CO₂ that could saturate the formation brine volume. Since CO₂ solubility in brine only decreases by 25% for every 100,000 ppm TDS (Enick and Klara, 1990; Celia et al., 2015) it is relatively constant over wide regional areas and can be extrapolated to large subsurface volumes.

4.4 ECONOMIC, ENVIRONMENTAL, AND LOGISTICAL CONSIDERATIONS

This section highlights a few of the issues beyond the geologic parameters that go into the volumetric estimation.

4.4.1 Economics

Building and maintaining offshore infrastructure is considerably more expensive than onshore. Operational costs including drilling, transport, and injection costs are also more expensive offshore. If new wells are drilled, the estimated cost of drilling per foot exceeds $2,000 offshore compared to $200–400 per foot onshore (Vidas et al., 2012). Also, while many sources of CO₂ emissions lie along the coast, transport of compressed CO₂ via pipelines to offshore sites can be costly.

There are numerous ways injection of CO₂ into the subsurface offshore could affect economic resources. Brownfields (i.e. depleted fields) on the shelf could benefit from enhanced oil recovery (EOR) using CO₂ injection, which could boost oil and gas extraction from reservoirs, potentially extending the life and profitability of offshore fields as well as offsetting the costs associated with CO₂ storage (Bachu, 2008). An economic risk of storing CO₂ offshore, however, is that it may impact the quality of tapped and untapped resources in nearby reservoirs if it should leak to those producing reservoirs. Further, surface economic interests such as commercial fisheries, sensitive ecosystems, and tourist destinations could be in jeopardy if injected CO₂ finds its way to the water column and surface (Offshore Storage Technologies Task Force, 2015).

4.4.2 Environment

In addition to marine economic interests, environmental impacts must be considered with carbon storage. Research prior to the publication of the 2015 CSLF Offshore Report (OSTF, 2015) focused on the impact of atmospheric CO₂ absorption into ocean waters on sensitive marine ecosystems (Secretariat, 2014; Widdicombe et al., 2013). Since then, researchers have begun investigating the potential effects of localized CO₂ leakage. Offshore Norway has been the site of two successful carbon storage projects, Snøhvit and Sleipner, for nearly 20 years, and little to no leakage has been detected (Eiken et al., 2011). Most monitoring methods in Norway are deep-focused monitoring methods in an attempt to detect reservoir level perturbations. A purposefully
leaky site was created in Ardmucknish Bay, Scotland, to evaluate the impact of CO₂ leakage on ecosystems and the effectiveness of various shallow-focused monitoring techniques. Lessons learned at the sites in Norway, from the Ardmucknish Bay experiments, and observations from natural CO₂ seeps were incorporated into a 2015 report on best environmental risk assessment practices for sub-sea CO₂ storage by the European Union’s ECO₂ project (Wallmann et al., 2015). The IEAGHG (2015) report reviews the deep- and shallow-focused monitoring techniques for offshore carbon storage projects. These provide good overviews of the best practices and recommended monitoring techniques to use for protecting the environment above offshore carbon storage sites, as well as some insight into the potential environmental impact of leakage at those sites.

4.4.3 Logistics

Offshore, data collection in select areas may be less expensive than onshore. Geology in petroliferous areas is typically well understood due to the large amount of data collected by industry, whereas non-producing saline reservoirs are often data-poor even when proximal to a petroleum reservoir. A smaller number of regulators offshore makes permitting easier. In offshore three-dimensional (3-D) seismic datasets, areas of potential leakage can potentially be identified on a seismic line as washouts in the data due to dewatering or gas clouds perturbing the sediment or water column, or as seafloor expressions (Cathles et al., 2010; Huang et al., 2009; Judd and Hovland, 2007; Offshore Storage Technologies Task Force, 2015). In addition, monitoring CO₂ plume migration offshore will be easier and less expensive than onshore through the use of four-dimensional (4-D) seismic imaging of the plume itself (Offshore Storage Technologies Task Force, 2015). Further, mature monitoring technologies, such as a passive seismic array, are progressively easy to deploy and the resulting data is easier to interpret compared to noisy onshore seismic data. However, fewer well penetrations in non-petroliferous areas means less is generally known about the other subsurface parameters, such as those that drive reservoir quality (i.e. porosity, permeability, sand/shale ratio, etc.).
5. DISCUSSION OF AN OFFSHORE METHODOLOGY

The equations used in the DOE methodologies for carbon storage resource estimation are flexible formulas that can be used at multiple scales. For any of the available methods, however, the quality of the estimates is heavily dependent on the inputs available. In order to assess the carbon storage resource offshore, the current equations and efficiency factors for saline formations and oil and gas reservoirs are sufficient for regional site screening estimates. As recommended by Goodman et al. (2016), the volumetric approach for estimating storage resources offshore should be accompanied by a spatial prospectivity analysis that indicates the suitability of the area for carbon storage, and the potential uncertainty in the resource estimate. At the least, prospectivity analyses at all scales should account for the nature of the reservoir and the integrity of the seal in the zones of interest for carbon storage.

The input terms for the volumetric equations, \( A_t, h_g, \phi_{tot}, \rho_s, \) and \( E_{saline} \), reflect the properties of the target region or reservoir and are derived from specific reservoir data or analogue data from similar geologic settings. These parameters may range from single-value data averaged over a region to values chosen probabilistically from a distribution, depending on the data available. The greatest change to the selection of input terms for the volumetric equations, when evaluating offshore areas, should come during the evaluation of the area term, \( A_t \), and this assessment can be assisted by a prospectivity analysis. For a reasonable assessment of a storage resource, the area assessed should be chosen with thought to the differences between onshore and offshore environments. Other input terms, such as thickness \( (h_g) \) and porosity \( (\phi_{tot}) \), may be limited by the available data. At a regional scale with limited data, the efficiency factors used in the DOE methodologies represent a broad range of parameters from depositional environments that are analogues to offshore environments. There is data to constrain most U.S. offshore storage areas of interest for the area efficiency term, \( E_A \).

This study recommends that the offshore resource estimation should go beyond the volumetric estimation and include some evaluation of the economic and human factors in the area of interest, similar to the approaches taken by Norway (Halland et al., 2014), Australia (Bradshaw et al., 2011; Spencer et al., 2011), Brazil (Ketzer et al., 2015), China (Jian, 2014), and Japan (Ogawa et al., 2011; Takahashi et al., 2009). By using a geospatial approach, these additional factors can be layered with geologic parameters and incorporated into the prospectivity analysis. The geologic conditions of the reservoir and seal should be suitable for storage of CO\(_2\). The requirements of the current methodologies, as discussed in section 3, are: 1) pressure and temperature conditions must be such that CO\(_2\) will be in a supercritical or dense-liquid state, which is generally taken to occur when formation depths are greater than 800 m (Goodman et al., 2011; NETL, 2015); 2) formation water is not potable, where potable ground water is defined as having less than 10,000 ppm TDS by the Safe Drinking Water Act (EPA, 2010); and 3) a caprock is present to act as a seal. Offshore, since there are few potable aquifers, the TDS requirement is generally not a problem (Schrag, 2009). However, the presence of the water column, as well as variable temperature and pressure gradients in basins such as the Gulf of Mexico, suggest that if data are available, an assessment of CO\(_2\) density distribution should be used as criteria to define the area of interest, rather than applying the 800 m rule of thumb.

The presence and integrity of the seal or caprock should also be evaluated offshore and used to inform \( A_t \). Meckel et al. (2014) conducted a detailed analysis of the Texas Gulf Coast; they used available geologic data to map both the reservoir and the seal, and they recommend that high-resolution 3-D seismic data be used to characterize the subsurface and the integrity of the seal.
At the basin or regional scale, regionally-extensive shales may be distinguished as sealing units, and proxies such as hydrocarbon well locations, seeps, vents, and mud volcanoes, known faults, tectonic activity, or active salt tectonics may indicate that the seal is compromised or unstable in a given area. It is often not known how exactly these factors may affect the storage resource; for instance, the amount of throw on a fault may provide a seal in some places and a leakage pathway in others, such that a heavily-faulted region may be considered less suitable for carbon storage (Halland et al., 2014; Vangkilde-Pedersen et al., 2009c). Areas with a great number of wells, or very old wells, may be subject to compromised seal integrity: if an injected CO₂ plume reaches an unplugged, improperly abandoned, or defective well, the plume could leak through the leaking wellbore regardless of the quality of the sealing unit. Due to abundant available data, well-characterized geology, and proven traps, depleted oil and gas fields offshore provide areas with much less uncertainty than deep saline formations offshore, for which there is typically little data.

Another consideration is that although young, unconsolidated sediments offshore are mechanically weak, their ductile behavior allows natural sealing of faults and man-made boreholes in favorable pressure conditions. Also, there is less likelihood that the unconsolidated sediment package has experienced faulting and fracturing because its deformation behavior is ductile, not brittle (Offshore Storage Technologies Task Force, 2015). However, pressure generation at depth due to disequilibrium compaction, clay dewatering, hydrocarbon generation, and other processes, causes overpressure in sediments undergoing burial. This may fracture the sealing unit itself, or cause leakage pathways along critically stressed faults. Overpressure results in a narrow pressure window for CO₂ injection that impacts the favorability of a formation for CO₂ storage, potentially requiring low injection rates or other forms of pressure management to maintain pressures below the fracture gradient. This reduces the total amount of CO₂ that can be stored and increases the operating risk, but does not diminish the capacity of the formation if pressure management solutions are employed.

Overpressured zones will have important implications on the area and area efficiency terms in the equation. If closed, overpressured sections are to be avoided, both the total area of the formation of interest and the percentage of available space, Eₐₐ/ₐₐ, will be less. If the assumption is made that pressure can be managed such that adequate injectivity is possible despite high initial pressures, then the efficiency terms describing area, thickness, and porosity will be greater. Fluid and pressure management strategies include brine extraction and/or pre-CO₂ injection brine production (Buscheck et al., 2016; Birkholzer et al., 2015).

Long-term trapping mechanisms such as residual storage capacity, dissolution storage, and mineral trapping are ignored in the DOE volumetric method at the site screening level. Thus, parameters that affect these mechanisms, such as fluid chemistry and mechanics, will have no effect on the volumetric equation at the high level but ultimately are non-negligible at the local level. Storage in closed systems will primarily utilize buoyancy trapping in the near term, but will use dissolution and capillary trapping in the long term, assuming undersaturated water can circulate in the system. Carbon storage in formations with variable salinity adds to uncertainty of solubility trapping capacity. Deeper zones may have less saline water due to the influx of fresh water from the dewatering of clays at depth, thus increasing solubility trapping of CO₂, but brine contact with salt diapirs shifts salinity to the high side which will have the opposite effect. As more data become available and sites are selected for further study, these storage mechanisms
should be considered for accurate site-specific capacity estimations, injectivity forecasts, and long-term storage security.

As part of a prospectivity analysis, human and environmental factors should be considered to some degree in order to identify effective areas for carbon storage. Resource assessments which consider current technologies can incorporate reservoir proximity to CO₂ emitting sources, infrastructure and data availability, and untapped hydrocarbon resource potential. This evaluation is important for understanding the economics and feasibility of CO₂ storage in today’s financial environment. Reevaluating these parameters based on advances in technology or decreased costs are important for maintaining up-to-date resource assessment values. Some operations are considerably more expensive in the offshore environment compared to onshore. In terms of the volumetric formula, mapping environmentally sensitive areas or economically important areas such as fisheries and tourist destinations can impact A_T especially if these areas are restricted by regulation. Prospectivity analyses that effectively eliminate certain areas due to their environmental sensitivity, economic resource potential, and/or lack of infrastructure will have effects on the Area term in the volumetric formula. Furthermore, mapping these parameters can help identify areas most susceptible to leakage events.
6. **FUTURE WORK**

Current carbon storage resource estimation methodologies focus on carbon storage potential in onshore deep saline formations and depleted oil and gas reservoirs. The current DOE methodology is appropriate for high-level volumetric resource estimation at both regional and local scales over long time periods in the offshore environment; however, implementing the methodology for offshore resources will require adaptation of a geospatial prospectivity component that will aid in both incorporating sparse geological data from offshore systems and screening for suitable storage sites based on infrastructure and other environmental and geological constraints.

6.1 **APPLYING ONSHORE CALCULATIONS TO ESTIMATE OFFSHORE CO₂ STORAGE EFFICIENCY AND CAPACITY**

The volumetric calculations of top-level storage resources are identical despite key differences between offshore and onshore systems (Section 4). The efficiency factor calculation explained in Section 3.3.1 will be used to estimate carbon storage efficiency offshore (Goodman et al., 2011). The resulting efficiency factor, will then be implemented in the DOE methodology, also outlined in Section 3.3.1, to calculate the total mass of CO₂ that can be stored offshore.

The differences between offshore and onshore sediments are represented in the available data. Therefore, although the same volumetric equations will be used to measure efficiency and capacity, the input data values are expected to differ. Offshore real data was sourced from petrophysical well logs, as well as regional Bureau of Ocean Energy Management (BOEM, 2016) datasets to calculate efficiency values pertaining to thickness, area, and porosity. Furthermore, information from literature and expert knowledge will be used to drive how input parameters are defined.

These calculations are automated using customized scripts in Python, which will implement such features as Monte Carlo logic to quantify estimated distributions for both saline efficiency and total storable CO₂. Saline efficiency and total storable mass of CO₂ will be estimated for several offshore geologic domains in the Gulf of Mexico. The domains are results of NETL’s Subsurface Trend Analysis (STA), an effort by NETL to identify broad spatial trends and correlations among subsurface geological characteristics (Mark-Moser et al., 2018). The aforementioned scripts will be trained using the known data for the selected domains, then expanded to estimate potential saline efficiency and total storable mass for larger regions, including the offshore Gulf of Mexico.

6.2 **GEOSPATIAL ANALYSIS FOR OFFSHORE STORAGE PROSPECTS**

In order to further assess offshore carbon storage prospects beyond volumetric calculations, this study recommends utilizing various geospatial analytical approaches. Volumetric analyses alone provide incomplete evaluation of carbon storage potential across all scales because they omit logistical and geological complexities; the U.S. DOE Best Practices guidance and others recommend exploring additional analytics (Halland et al., 2014; Spencer et al., 2011; NETL, 2013). Geospatial applications may be broadly useful to offshore carbon storage as prospectivity analyses, uncertainty assessments, and information organization and evaluation. Key areas of carbon storage assessment that may be addressed using geospatial tools include:

- Analysis of data density
• Evaluation of subsurface uncertainty
• Identification of reservoirs and fields with carbon storage potential
• Trends of subsurface properties such as pressure, temperature, porosity and permeability
• Availability and volume of carbon storage resources
• Geological characterization at multiple scales
• Impact and risk assessment

A suite of geospatial tools developed at NETL have potential use in these areas: Cumulative Spatial Impact Layers (CSIL) (Romeo et al., in progress; Bauer et al., 2015), Spatially Weighted Impact Model (SWIM), Variable Grid Method (VGM), STA, and the Subsurface Databook (Bauer et al., 2015; Bauer and Rose, 2015; Rose et al., in review; NETL, 2016b). Application of these tools have thus far been for risk assessment and hazard mapping, but they can be modified for carbon storage assessments. CSILs and SWIM allow the user to analyze spatial data during prospectivity analysis to assess data quality and quantity. Essentially, the CSIL or SWIM layer could combine the ranking system with the spatially explicit geologic data, thereby producing a map to visually indicate areas where carbon storage has the highest chance of success. The VGM assesses uncertainty based on completeness and/or clustering of data, producing a visual representation of data density and availability in a given area. Reducing uncertainty in areas of low data density can be accomplished using the STA method, which utilizes statistical analyses of existing data in conjunction with a priori geologic knowledge of an area at any geologic scale. Guidance to previously collected data and analyses can be found in the Subsurface Databook, a capability within DOE FE’s Energy Data eXchange™, which composes information on areas, lease blocks and individual fields used in offshore oil and gas exploration and production.

6.3 MODIFYING EFFICIENCY FACTORS FOR OFFSHORE STORAGE

In open systems, the CO₂ storage mass is reduced by an efficiency factor (see Equation 2). In the DOE CO₂-Screen tool and in other publications (Goodman et al., 2016), efficiency factors are based on work by Gorecki et al. (2009) which utilizes data collected from multiple basins and depositional environments, primarily onshore. Due to the unconsolidated nature of offshore sediments in the depth range of interest, this study recommends future work to include developing more specific efficiency factors based on offshore formations of interest. Data are required to adequately determine the effect of compaction on CO₂ injection and storage efficiency. Bradshaw et al. (2007) note that many estimates (global and regional) are computed using highly generalized inputs for geologically complex environments. These generalizations can promote misleading capacity estimates with high uncertainty at regional scales both onshore and offshore. Peck et al. (2014) also stresses that efficiency factors must be used appropriately for reasonable estimations. For more detailed information on the derivation and application of efficiency factors, please consult Gorecki et al. (2009), Goodman et al. (2011), Peck et al. (2014), and Gorecki et al. (2015). The second effort of this project (Task 2) includes refining the wide range in efficiency factors for offshore environments, with special focus on incorporating publicly available data from the offshore Gulf of Mexico as a test case in calculating offshore-specific efficiency factors.
7. **SUMMARY**

Storage of carbon dioxide in offshore environments is gaining more attention in the U.S. and around the world due to the high potential storage capacity of offshore formations and the relative remoteness to human population centers and protected groundwater. The volumetric formulas used by the DOE carbon storage resource assessment methodologies can generally be used to evaluate offshore environments for carbon storage at the basin scale and regional scale, however, they will be most effective if accompanied by a prospectivity analysis below the regional scale. Offshore-specific factors that should be addressed in such an analysis include the water column’s influence on subsurface temperature and pressure, the overburden’s ability to seal and permanently trap buoyant CO₂, and the in-situ fluid’s ability to adjust to CO₂ injection either by displacement or dissolution. Beyond a geologic evaluation, an overall evaluation of any potential offshore storage resource should consider human and environmental concerns, such as the expense of creating new offshore infrastructure or repurposing existing infrastructure, risks to sensitive marine fisheries and environments.

This study recommends utilizing NETL’s geospatial toolsets including CSIL, SWIM, and VGM that can aid in prospectivity analysis, assessing the favorability of reservoir parameters, including the volume, porosity, and expected CO₂ density, the presence and integrity of the seal, including the probability of leakage pathways, and injectivity parameters, including: permeability, pressure, and geomechanical strength of the seal. NETL’s own geospatial tools can help the investigator visualize the important storage parameters and conduct a prospectivity analysis. Integrating spatial tools should result in more accurate, less uncertain offshore resource estimates.
8. REFERENCES


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