A workflow was developed to properly assess the CO₂ storage resource potential of a deep saline formation using the methodology proposed by the U.S. Department of Energy. To illustrate the workflow, the Minnelusa Formation of the Powder River Basin is used as an example of how a CO₂ storage resource methodology could be applied to a saline formation given varying levels of information. It is important to accurately estimate the effective volumetric CO₂ storage resource potential of a target formation, and new storage efficiency values are presented with the workflow.

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Peer-review under responsibility of the Organizing Committee of GHGT-12

Keywords: storage capacity, saline formations, methodology, CO₂ storage.

1. Introduction

Because of the concern over the growing amount of anthropogenic CO₂ emissions, using carbon capture and storage (CCS) to geologically store CO₂ is a key mitigation technique under consideration. The large volumes of CO₂ that would need to be stored in order to make a significant reduction in CO₂ emissions require the ability to have an accurate understanding of the CO₂ storage resource available in deep saline formations. The U.S. Department of Energy (DOE) established the Regional Carbon Sequestration Partnerships (RCSP) in 2003 to promote CCS in different regions of the United States and Canada and to determine and implement the technology, infrastructure, and regulations most appropriate to advance CCS. Part of this initiative included a characterization
effort to determine the storage resource potential of saline formations in order to support future CCS demonstration projects. To date, these efforts have determined that the United States and Canada have an estimated CO₂ storage resource potential of 2012 to 20,043 billion tonnes in deep saline formations [1]. Characterization efforts are ongoing, and estimates continue to be revised and refined as more data become available.

The interest in the geologic storage of CO₂ reinforces the importance of being able to accurately estimate the CO₂ storage resource potential of a given target formation. Conceptually, calculating the volumetric CO₂ storage potential of a given formation is a straightforward task; however, each formation evaluation is unique and can differ significantly in terms of scope, budget, and available data. Basic information needed to assess a formation for CO₂ storage potential includes a formation’s area, thickness, porosity, CO₂ density at reservoir conditions, and primary reservoir lithology. Other information such as salinity and distributions of porosity/permeability can further enhance the CO₂ storage estimate, if they are known. Depending on the quantity of basic data used to evaluate a saline formation, differing storage efficiency factors and their associated confidence intervals need to be applied to ensure the most accurate prediction possible.

Lithology, depth, boundary conditions, and salinity all have a large impact on a formation’s suitability for CO₂ storage. These parameters are also important in determining the portion of the formation that is amenable to CO₂ injection and storage, (i.e., the net-to-gross formation pore volume or $E_{\text{Geol}}$ [2]), and in choosing the appropriate storage efficiency term. The goal of this paper is to provide a step-by-step workflow to properly assess the CO₂ storage resource of a saline formation given varying levels of starting data. The workflow, terms, and concepts presented in this paper will provide the user confidence in performing CO₂ storage resource assessments, and help reduce under- or overestimation of the effective CO₂ storage resource potential of a target deep saline formation. For the purposes of this paper, the DOE National Energy Technology Laboratory (NETL) method was used [3]; however, a similar approach could be used for other volumetric approaches (e.g., Carbon Sequestration Leadership Forum, 2005 [4]). To help illustrate the workflow, three scenarios for the Minnelusa Formation of the Powder River Basin are presented. These examples demonstrate how a CO₂ storage resource estimate should be made for a saline formation with different levels of known information.

2. Methodology

The two most commonly used methodologies to determine storage are those developed by DOE NETL [1] and the Carbon Sequestration Leadership Forum (CSLF) [4]. These two methodologies have been compared and found to be equivalent provided the same assumptions are made and the efficiency terms properly applied [2]. The effective CO₂ storage resource potential of a targeted saline formation is estimated using a volumetric equation where the pore volume of the target formation is multiplied by a storage efficiency term and the density of the CO₂ at reservoir conditions:

$$M_{\text{CO}_2} = A \times h \times \varphi \times \rho_{\text{CO}_2} \times E$$  \hspace{1cm} (1)$$

Total area ($A$), gross formation thickness ($h$), and total porosity ($\varphi$) terms account for the total bulk volume of pore space available. The value for CO₂ density ($\rho$) converts the reservoir volume of CO₂ to mass. The storage efficiency factor ($E$) represents the fraction of the total pore volume that can be occupied by the injected CO₂.

Although volumetric methods such as this are straightforward, misapplications of the efficiency factors commonly occur and may ultimately lead to under- or overestimation of the effective storage resource potential of the formation under investigation. The choice of which efficiency terms to apply is directly related to the amount of information known about the formation’s area, thickness, porosity, and pressure boundary conditions.

The efficiency term ($E$) represents the percentage of the formation’s pore volume that can be occupied by CO₂. In open systems, the efficiency term represents the fraction of the geology that is amenable to storage and the portion of that pore space that CO₂ can occupy by displacing the original formation fluids during the course of injection ($E_{\text{f}}$) (Equation 2). The amenable geology is defined as the fraction of the total formation volume that has suitable geology for CO₂ storage ($E_{\text{geol}}$) and is a multiplicative combination of the net-to-total area ($E_{\text{nt}/A}$), the net-to-gross thickness ($E_{hnt/hg}$), and the effective-to-total porosity ($E_{\text{eff}/\varphi_{\text{t}}}$) (Equation 3). $E_{\text{geol}}$ is generally defined as the area where there is sufficient formation at a depth where CO₂ will remain in the supercritical state, typically around 800 meters, and where the salinity of the formation fluids is above the total dissolved solids (TDS) cutoff for
protected underground sources of drinking water (USDW) (10,000 ppm). It also excludes intervals in the formation with unsuitable geology for injection. The second factor contained in the $E_E$, the displacement efficiency ($E_D$), is split into the volumetric displacement efficiency ($E_{vol}$) and the microscopic displacement efficiency ($E_d$). The volumetric displacement efficiency is the combined fraction of the pore volume that can be contacted by CO$_2$ from injection wells and the fraction of the net thickness that is contacted by CO$_2$ from injection wells and the fraction of the net thickness that is contacted by CO$_2$ as a result of the density difference between the injected CO$_2$ and the formation fluids. The microscopic displacement efficiency represents the fraction of the contacted pore space that can be filled by CO$_2$ and is directly related to the irreducible water saturation.

$$E_E = E_{geot} \ast E_D$$  \hspace{1cm} (2)
$$E_{geot} = E_{A_n/A_t} \ast E_{h_n/h_g} \ast E_{\phi_{eff}/\phi_{tot}}$$  \hspace{1cm} (3)
$$E_D = E_{vol} \ast E_d$$  \hspace{1cm} (4)

To assist in identifying which efficiency factor to use for the volumetric calculation, a workflow was created to guide users in correctly assessing the formation under investigation (Fig. 1). To illustrate the workflow, the upper Minnelusa Formation of the Powder River Basin is used as an example of how an effective CO$_2$ storage resource estimate could be determined from a saline formation with different levels of information. A 3-D geologic model of this formation was constructed for a study conducted for the IEA Greenhouse Gas R&D Programme (IEAGHG) [5]. The purpose of that study was to compare CO$_2$ storage efficiency in deep saline formations estimated using both volumetric and dynamic methodologies. The data from the IEAGHG study provide the baseline data for the scenarios presented in this paper.

Three scenarios are presented: 1) if only the gross formation properties are known, 2) if all of the net-to-gross properties of the formation are known, or 3) if only the area amenable to CO$_2$ storage is known (net-to-gross property is known, with the other net-to-gross properties unknown. These are common scenarios that occur in CO$_2$ storage calculations. Those investigating potential target formations may know very little about the formation (Scenario 1), or they may be investing a large amount of time with abundant information known (Scenario 2). These two scenarios are straightforward in terms of procedure and which storage efficiency factor should be used. However, it is also common for investigators to have information on the formation’s depth and salinity, which allows them to derive the net area (Scenario 3). In this case, the more conservative storage efficiency factor shouldn’t be used because the net-to-gross factor is known, but there is not enough information known to apply the larger efficiency factors. As noted in Ellett and others [6], a simple disaggregation of the individual efficiency terms is not accurate. Therefore, the new efficiency factors shown in the workflow (Fig. 1) should be used.

3. Scenarios

As described above, each scenario is presented using the upper Minnelusa Formation of the Powder River Basin. The upper Minnelusa Formation is a clastic, open boundary formation, and each scenario assumes a different combination of information is known through literature review, data gathering, or geologic modeling efforts. In order to inject CO$_2$ into a formation, the salinity must be above 10,000 ppm and the depth must be below 800 meters. If these two parameters are not met, the formation is not eligible (suitable) to be a storage target. If the reservoir meets these two requirements, the formation’s total area, gross thickness, average porosity, and density of CO$_2$ at reservoir conditions must be determined (as shown in Fig. 1).

Each scenario’s parameter values used to calculate the CO$_2$ storage potential in the upper Minnelusa Formation are found in Tables 1–3. Table 1 shows the parameters that are used to calculate the total pore volume. For Scenarios 1 and 3, this involves simply multiplying the thickness, porosity, and area. Scenario 2 has values derived from a 3-D geocellular model, and pore volumes are determined through the model for each individual cell across the model.
Fig. 1. A workflow to estimate CO₂ storage resource in deep saline formations.
There are key differences to note between the three scenarios. Scenario 2 has a lower average porosity value (3.35%) that was derived through the geocellular model. This value includes parts of the formation that are not amenable to CO₂ storage, whereas the 12% porosity value used in Scenarios 1 and 3 reflect only the part of the formation that is amenable to storage. The low porosity value in Scenario 2 results in a significantly lower total pore volume.

Scenario 3 involves a notable difference in the knowledge regarding area of the formation. In Scenarios 1 and 2, the Minnelusa Formation total area is known, regardless of whether the formation is deep enough or the salinity is high enough. In Scenario 3, only the net (target) area where the formation is deep enough and the salinity is high enough is analyzed. In other words, the total area of the formation is not used, and only the area meeting the CO₂ injection requirements is used to calculate pore volume.

Table 2 shows the net-to-gross parameters that are known for each scenario. In Scenario 2, all the ratios for the key parameters are known which allows for the calculation of E_{geo} and, consequently, higher E_{saline} values to be used. In Scenarios 1 and 3, not all of the net-to-gross parameters are known, so E_{geo} cannot be calculated. However, Scenario 3 does have the net-to-gross area as described above, so the total pore volume is equal to the net pore volume and a slightly higher E_{saline} value (Table 3, Fig. 1) can be used to reduce the amount of pore space used for CO₂ storage. This E_{saline} value in Scenario 3 accounts for the unknown net-to-gross thickness and porosity values.

Table 3 shows the E_{saline} values, CO₂ density, and the CO₂ storage values. Again, Scenario 2 has values derived from a 3-D geocellular model, and calculations are completed for individual cells across the model area.

3.1. Scenario 1

Scenario 1 represents the most basic approach to assessing the CO₂ storage of a formation. A formation being evaluated may have little information available, or those performing the assessment may have little time or resources to fully evaluate the formation.

In order to estimate the CO₂ storage, the formation’s average thickness, average porosity, and extent should be known. For Scenario 1, these values are determined through a literature review (Table 1). The full extent of the Minnelusa is not known in this scenario, and the literature review indicates that the formation is roughly the same area as the Powder River Basin at 51,800 km². Since the net-to-gross data are unknown, the most conservative low, mid, and high case values (P10, P50, P90) for E_{saline} in a clastic formation must be used (Table 3, Fig. 1). Further, literature review found pressure and temperature values for the upper Minnelusa, resulting in an estimated average CO₂ density. The CO₂ storage in this scenario ranged from 1505 to 15,936 million tonnes (Table 3).

3.2. Scenario 2

Scenario 2 represents a more thorough assessment where, unlike Scenario 1, all of the parameters are known. The formation is well understood, allowing for a more rigorous formation evaluation and a more accurate CO₂ storage estimate. Typically, in order to determine the necessary net-to-gross terms, a characterization effort including construction of a 3-D model is used.

The 3-D model is constructed from available data sets and literature. Unlike Scenario 1, the formation extent and thickness were mapped by picking log tops to create detailed structure maps throughout the basin. A petrophysical workflow was performed to determine how porosity changes because of compaction and facies variations. The petrophysical results were distributed geostatistically to create a 3-D model of the formation capturing the overall heterogeneity.

In contrast with Scenario 1, the net values for area, thickness, and porosity can be determined. The net area for the upper Minnelusa excludes areas where water salinity is <10,000 TDS and the measured depth is <800 meters. Net thickness excludes low porosity shales or tight dolomite where CO₂ could not be stored. Net porosity includes a cutoff based on a permeability/porosity cross-plot. Knowing these parameters allows for using higher efficiency factors than were used in Scenario 1 (Tables 2 and 3). The CO₂ storage in this scenario ranged from 4506 to 14,615 million tonnes (Table 3).
3.3. Scenario 3

Similar to Scenario 2, the formation’s areal extent and thickness was mapped by picking log tops to create detailed structure maps throughout the basin. In Scenario 3, the part of the formation amenable to CO₂ injection (i.e., target area) is the only area used in the calculation, while the thickness and porosity net-to-gross parameters are unknown. Unlike Scenario 2, porosity is assumed from the literature review to be 12% as in Scenario 1.

Since the target area is known, the formation’s total area is equal to the net area that is known to have salinity greater than 10,000 TDS and is deeper than 800 meters (Table 1). This means the net pore volume is equal to the total pore volume, and the volume can apply a revised efficiency value that accounts for the missing net-to-gross thickness and porosity parameters (Table 3, Fig. 1). The estimated average CO₂ density used was the same as Scenario 1. The CO₂ storage in this scenario ranged from 5173 to 30,430 million tonnes (Table 3).

Table 1. Scenario parameters used to calculate total pore space.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Thickness, m</td>
<td>76</td>
<td>73</td>
<td>73</td>
</tr>
<tr>
<td>Average Porosity, %</td>
<td>12</td>
<td>3.35</td>
<td>12</td>
</tr>
<tr>
<td>Total Area, km²</td>
<td>51,800</td>
<td>70,300</td>
<td>58,350</td>
</tr>
<tr>
<td>Total Pore Volume, km³</td>
<td>472.4</td>
<td>173.9</td>
<td>511.1</td>
</tr>
</tbody>
</table>

Table 2. Scenario net-to-gross parameters used to determine efficiency values (E_{saline} and E_{saline}) used.

<table>
<thead>
<tr>
<th>Net-to-Gross Parameters</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area, %</td>
<td>Unknown</td>
<td>0.87*</td>
<td>1</td>
</tr>
<tr>
<td>Thickness, %</td>
<td>Unknown</td>
<td>0.84</td>
<td>Unknown</td>
</tr>
<tr>
<td>Porosity, %</td>
<td>Unknown</td>
<td>0.62</td>
<td>Unknown</td>
</tr>
<tr>
<td>Net Pore Volume, km³</td>
<td>–</td>
<td>78.8</td>
<td>511.1</td>
</tr>
</tbody>
</table>

*Percentage in the model was volume, not area.

Table 3. Scenario efficiency, density, and storage values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_{saline}, Values, P10, P50, P90, %*</td>
<td>0.51, 2.0, 5.4</td>
<td>7.4, 14, 24</td>
<td>1.62, 4.41, 9.53</td>
</tr>
<tr>
<td>Average CO₂ Density, kg/m³</td>
<td>624.7</td>
<td>773</td>
<td>624.7</td>
</tr>
<tr>
<td>P10 CO₂ Storage, million tonnes</td>
<td>1505</td>
<td>4506</td>
<td>5173</td>
</tr>
<tr>
<td>P50 CO₂ Storage, million tonnes</td>
<td>5902</td>
<td>8525</td>
<td>14,081</td>
</tr>
<tr>
<td>P90 CO₂ Storage, million tonnes</td>
<td>15,936</td>
<td>14,615</td>
<td>30,430</td>
</tr>
</tbody>
</table>

*P10, P50, P90 values given in order.

4. Summary

As shown in the three different scenarios, the calculation of the amount of CO₂ storage potential for a formation can vary significantly depending upon the information known. The workflow presented (Fig. 1) gives storage efficiency values to use if net-to-gross area (target area) or net-to-gross area and thickness values are known for a formation [7]. These updated efficiency values will increase the accuracy of storage estimates as more appropriate efficiency values can be used based upon the amount of information known. Misapplication of storage efficiency values could lead to misinterpretation of the formation and may limit future studies if a formation is regarded as being “low” in storage potential. Conversely, the opposite could be true where a formation is seen as having “high” potential for storage when, in fact, the incorrect efficiency values were applied.

Scenarios were presented to show the applicability of using the developed workflow to properly assess the correct efficiency term for a formation based on the amount of data available. Although each scenario has a storage mass calculated, each differs because of the amount of data and the geologic knowledge of the reservoir. Scenario 1 represents a typical quick-look assessment using the bare minimum of data. These values can be found with relatively little effort in publications by the state geological surveys or peer-reviewed journals. Because no net-to-gross terms are known, the efficiency factors are small and take a conservative approach to account for the unknown data, resulting in higher overall uncertainty in the assessment.
Scenario 2 represents the most thorough assessment, and in most cases like this, a 3-D geologic model is built to perform dynamic simulations to investigate formation injection scenarios. Although Scenario 2 is the more accurate assessment, it is imperative that the correct efficiency term is applied, as applying the wrong efficiency term would essentially eliminate the net-to-gross area twice, thereby drastically reducing the overall storage resource estimate unnecessarily.

Scenario 3 represents a situation where the target area is known and an updated storage efficiency value needs to be used. This case is typical of many formation evaluations, and improves upon the basic assessment of Scenario 1. This scenario is important because investigators need to know that a formation meets the depth and salinity requirements, and if they do have that information, then they very likely know the extent of the formation that is amenable to the CO₂ injection. With this information available, then the updated storage efficiency values become important and allow for a more accurate storage calculation.

While Scenarios 1 and 3 are more of a characterized storage resource estimate and Scenario 2 is an effective storage resource estimate (Fig. 2), all three scenarios have value and can give reasonable estimates, provided their limitations are taken into consideration. For example, Scenario 1 represents a screening-level assessment that may be useful for decision makers to determine where to invest further characterization efforts.

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**Fig. 2. CO₂ storage classification framework [2].**
Acknowledgements

A special thanks to Angela Goodman of DOE for providing the intermediate storage efficiency values shown in Fig. 1.

This material is based on work supported by DOE NETL under Award Nos. DE-FC26-05NT42592, DE-FE0009114, and Cooperative Agreement No. DE-FC26-08NT43291. This work was also prepared with the support of the IEA Greenhouse Gas R&D Programme under reference IEA/CON/13/208.

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