Comparison of CO$_2$ Storage Resource Methodologies

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U.S. DEPARTMENT OF ENERGY • OFFICE OF FOSSIL ENERGY
NATIONAL ENERGY TECHNOLOGY LABORATORY
CARBON STORAGE PROGRAM with ARRA Projects

**Infrastructure**
- Regional Carbon Sequestration Partnerships
  - Characterization
  - Validation
  - Development

**Other Small and Large-Scale Projects**
- ARRA: Development of Technology Transfer Centers
- ARRA: Site Characterization

**Benefits**
- Human capital
- Stakeholder networking
- Regulatory policy development
- Visualization knowledge center
- Best practices development
- Public outreach and education

**Core R&D**
- Geologic Storage Tech
- Simulation and Risk Assessment
- Monitoring, Verification, Accounting, Assessment
- CO₂ Use and Reuse
- NETL ORD Focus Area
- ARRA: University Projects

**Benefits**
- Reduced cost of CCS
- Tool development for risk assessment and mitigation
- Accuracy/monitoring quantified
- CO₂ capacity validation
- Indirect CO₂ storage

**Global Collaborations**
- North America Energy Working Group
- Carbon Sequestration Leadership Forum
- International Demonstration Projects
  - Canada (Weyburn, Zama, Ft. Nelson)
  - Norway (Sleipner and Snovhit)
  - Germany (CO2Sink)
  - Australia (Otway)
  - Africa (In-Salah)
  - Asia (Ordos Basin)

**Benefits**
- Knowledge building
- Project development
- Collaborative international knowledge
- Capacity/model validation
- CCS commercial deployment

**Estimating CO₂ Storage in Geologic Formations**
High-Level Estimates of CO$_2$ Storage Potential
National, Regional, Basin, and Formation Scale

- Assess potential for **CCUS technologies** to reduce CO$_2$ emissions
- Broad **energy-related government policy and business decisions.**
- Identify potential regions to successfully implement CCUS technologies
- High degree of **uncertainty**:
  - simplifying assumptions
  - deficiency or absence of data
  - natural heterogeneity of geologic formations
  - undefined rock properties
  - scale of assessment
  - Inconsistent terminology
- Site characterization will allow for the **refinement** of high-level CO$_2$ storage resource estimates and development of CO$_2$ storage capacities.
- Until such detailed characterization can be documented, **dependable** high-level CO$_2$ storage estimates are essential to ensure **successful** widespread deployment of CCUS technologies
## Existing CO\textsubscript{2} Storage Estimates

*Intergovernmental Panel on Climate Change, 2005*

Table 5.2 Storage capacity for several geological storage options. The storage capacity includes storage options that are not economical.

<table>
<thead>
<tr>
<th>Reservoir type</th>
<th>Lower estimate of storage capacity (GtCO\textsubscript{2})</th>
<th>Upper estimate of storage capacity (GtCO\textsubscript{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil and gas fields</td>
<td>675\textsuperscript{*}</td>
<td>900\textsuperscript{*}</td>
</tr>
<tr>
<td>Unminable coal seams (ECBM)</td>
<td>3-15</td>
<td>200</td>
</tr>
<tr>
<td>Deep saline formations</td>
<td>1000</td>
<td>Uncertain, but possibly 10\textsuperscript{4}</td>
</tr>
</tbody>
</table>

\textsuperscript{*} These numbers would increase by 25\% if “undiscovered” oil and gas fields were included in this assessment.
Existing CO$_2$ Storage Estimates

Inconsistent CO$_2$ Storage Estimates up to 2006

- Highly variable and contradictory
Examples of Recent CO$_2$ Storage Estimates (post 2007)

Atlas I - March 2007
Atlas II - November 2008
Atlas III - November 2010
Atlas IV – November 2012

Distributed by:
- **Hard-copy**: CCUS Atlas of the United States and Canada
- **Web-served** geographic information system: NATCARB

U.S. Emissions ~ 6 GT CO$_2$/yr (all sources)

Examples of Recent CO$_2$ Storage Estimates (post 2007)

- **Oil and Gas Fields**: 143-155 GT CO$_2$ Storage Resource
- **Saline Formations**: 1,653 - 20,213 GT CO$_2$ Storage Resource
- **Unmineable Coal Seams**: 60-117 GT CO$_2$ Storage Resource
- **Basalt Formations**
- **Organic-Rich Shale**
Examples of Recent CO₂ Storage Estimates (post 2007)

North American Carbon Atlas Partnership

First coordinated effort between Canada, Mexico, and the United States to jointly publish a resource of data and information on CCS technologies, pressing issues, and current progress toward solutions

• NACAP’s Objective:
  – Identify, gather, and **share** data of CO₂ sources and geologic storage potential

• Development of this GIS-based CO₂ sources and storage database

• 3 North American Products (April 2012):

| CO₂ Storage Resources Estimates for Saline Formations in North America (Gigatonnes) |
|-------------------------------------------------|----------------|-----------------|----------------|
|                                                 | Canada         | Mexico          | United States  |
|                                                 | Low Estimate   | High Estimate   | Low Estimate   |
| Total                                           | 28             | 296             | 100            |
|                                                 | 1,610          | 20,155          |                |

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Examples of Recent CO$_2$ Storage Estimates (post 2007)


Figure-2 Comparison of estimated CO$_2$ storage capacity for each storage category in Japan.
Examples of Recent CO$_2$ Storage Estimates (post 2007)

Examples of Recent CO$_2$ Storage Estimates (post 2007)

<table>
<thead>
<tr>
<th>Formation</th>
<th>Area [km$^2$]</th>
<th>Porosity [%]</th>
<th>Net gross ratio [%]</th>
<th>$\rho_{CO_2}$ [kg/m$^3$]</th>
<th>Storage capacity [Mt]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Cretaceous</td>
<td>24,562.0</td>
<td>20.5</td>
<td>40</td>
<td>800</td>
<td>7,646.9</td>
</tr>
<tr>
<td>Lower Jurassic</td>
<td>70,106.0</td>
<td>17.3</td>
<td>60</td>
<td>700</td>
<td>43,825.7</td>
</tr>
<tr>
<td>Lower Triassic</td>
<td>112,036.0</td>
<td>9.7</td>
<td>70</td>
<td>600</td>
<td>26,494.1</td>
</tr>
</tbody>
</table>

Deep aquifers and geological structures suitable for CO$_2$ storage

Time Dependency of Trapping Mechanisms Involved in CO$_2$ Geological Storage

Operating Time Frame

Storage Security

**CO₂ Storage Classification**

### 2010 DOE Storage Resource Estimates

<table>
<thead>
<tr>
<th>Petroleum Industry</th>
<th>CO₂ Geological Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reserves</strong></td>
<td>Capacity</td>
</tr>
<tr>
<td>On Production</td>
<td>Active Injection</td>
</tr>
<tr>
<td>Approved for Development</td>
<td>Approved for Development</td>
</tr>
<tr>
<td>Justified for Development</td>
<td>Justified for Development</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Contingent Resources</th>
<th>Contingent Storage Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development Pending</td>
<td>Development Pending</td>
</tr>
<tr>
<td>Development Unclarified or On Hold</td>
<td>Development Unclarified or On Hold</td>
</tr>
<tr>
<td>Development Not Viable</td>
<td>Development Not Viable</td>
</tr>
</tbody>
</table>

### CSLF Techno-Economic Resource Pyramid

- *Increased certainty of storage potential*
- *Increasing cost of storage*

### IEA-GHG Storage Classification

- **Theoretical Storage Resource**
- **Characterized Storage Resource**
  - Practical Storage Capacity
  - Proved
  - Probable
  - Possible
- **Contingent Storage Resource**
- **Unusable Storage Resource**
- **Uncharacterized Storage Resource**

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Comparison of CO₂ Storage Methodologies for Saline Formations

- **2010 Atlas** presents national scale CO₂ storage resource estimates of how much CO₂ can be stored in deep brine-filled formations.
- How do other CO₂ storage estimates compare for different methodologies?
- Trapping Mechanisms Considered?
- Scale
  - Country?
  - Basin?
  - Regional?
  - Site Specific?

### 2010 CO₂ Resource Estimates by Partnership

<table>
<thead>
<tr>
<th>Partnership</th>
<th>Low (Billion Metric Tons of CO₂)</th>
<th>High (Billion Metric Tons of CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big Sky</td>
<td>221</td>
<td>3,041</td>
</tr>
<tr>
<td>MGSC</td>
<td>12</td>
<td>160</td>
</tr>
<tr>
<td>MRCSP</td>
<td>46</td>
<td>183</td>
</tr>
<tr>
<td>PCOR</td>
<td>165</td>
<td>165</td>
</tr>
<tr>
<td>SECARB</td>
<td>908</td>
<td>12,527</td>
</tr>
<tr>
<td>SWP</td>
<td>219</td>
<td>3,013</td>
</tr>
<tr>
<td>WESTCARB</td>
<td>82</td>
<td>1,124</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,653</strong></td>
<td><strong>20,213</strong></td>
</tr>
</tbody>
</table>

**Saline Formations**

1,653 - 20,213 GT CO₂ Storage Resource

*Image of map showing North America with blue areas indicating saline formations.*
CO₂ Storage Methodologies for Open and Closed Systems

**Open**
- **DOE-NETL**: Methodology developed by the DOE/NETL is intended for external users such as the Regional Carbon Sequestration Partnerships in high-level assessments of potential CO₂ storage reservoirs in the US and Canada.
- **USGS**: Methodology developed by the USGS is intended to be used by the USGS’s geologists for assessments at scales ranging from regional to sub-basinal in which storage assessment units are defined on the basis of common geologic and hydrologic characteristics.
- **CGSS**: Methodology developed for the 2009 Queensland CO₂ Geological Storage Atlas is intended for policy makers.
- **Szulczewski et al. (2012)**: Methodology to account for fluid dynamics and injection-rate constraints for CO₂ storage.

**Closed**
- **Zhou et al. (2008)**: Methodology for quick assessment of CO₂ storage in closed saline formation.

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**References**
- **CSLF: Bachu et al. 2007**
- **USGS: Brennan et al. (2010)**
- **CGSS: Spencer et al. (2010)**
- **Szulczewski et al. (2012)**
- **Zhou et al. (2008)**
CSLF Effective Storage Capacity

- Stems from the Technical Group Taskforce on CO₂ storage estimates led by the Carbon Sequestration Leadership Forum.
- **Effective Storage Capacity**, called previously “Realistic Capacity” represents a subset of the theoretical capacity and is obtained by applying a range of technical (geological and engineering) cut-off limits to a storage capacity assessment, including consideration of that part of theoretical storage capacity that can actually be physically accessed (structural and stratigraphic trapping). This estimate usually changes with the acquisition of new data and/or knowledge. *Bachu et al. Int. J. Greenhouse Gas Control 1 (2007) 430-443*

- Open boundaries / formation scale

\[ M_{CO_2} = Ah\phi(1-S_{wirr})\rho_{CO_2}C_c \]

**IEA-GHG 2010 Saline Capacity Coefficients for the Formation Level**

<table>
<thead>
<tr>
<th>Lithology</th>
<th>P10, %</th>
<th>P50, %</th>
<th>P90, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clastics</td>
<td>1.86</td>
<td>2.70</td>
<td>6.00</td>
</tr>
<tr>
<td>Dolomite</td>
<td>2.58</td>
<td>3.26</td>
<td>5.54</td>
</tr>
<tr>
<td>Limestone</td>
<td>1.41</td>
<td>2.04</td>
<td>3.27</td>
</tr>
<tr>
<td>All</td>
<td>1.66</td>
<td>2.63</td>
<td>5.13</td>
</tr>
</tbody>
</table>


Volumetric Approach

• Saline Formation CO₂ Storage Resource Estimates

\[ G_{CO2} = A_t \, h_g \, \phi_{tot} \, \rho \, E_{saline} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_{CO2} )</td>
<td>M</td>
<td>Mass estimate of saline formation CO₂ storage resource.</td>
</tr>
<tr>
<td>( A_t )</td>
<td>L²</td>
<td>Geographical area that defines the basin or region being assessed for CO₂ storage.</td>
</tr>
<tr>
<td>( h_g )</td>
<td>L</td>
<td>Gross thickness of saline formations for which CO₂ storage is assessed within the basin or region defined by ( A_t ).</td>
</tr>
<tr>
<td>( \phi_{tot} )</td>
<td>L³/L³</td>
<td>Total porosity in volume defined by the net thickness.</td>
</tr>
<tr>
<td>( \rho )</td>
<td>M/ L³</td>
<td>Density of CO₂ evaluated at pressure and temperature that represents storage conditions anticipated for a specific geologic unit averaged over ( h_g ) and ( A_t ).</td>
</tr>
<tr>
<td>( E_{saline} )</td>
<td>L³/L³</td>
<td>CO₂ storage efficiency factor that reflects a fraction of the total pore volume that is filled by CO₂.</td>
</tr>
</tbody>
</table>

* L is length; M is mass

ATLAS 2010 Saline Efficiency

\[ E_{saline} = E_{An/At} \, E_{hn/hg} \, E_{\phi_e/\phi_{tot}} \, E_v \, E_d \]

<table>
<thead>
<tr>
<th>Lithology</th>
<th>( P_{10} )</th>
<th>( P_{50} )</th>
<th>( P_{90} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clastics</td>
<td>0.51%</td>
<td>2.0%</td>
<td>5.4%</td>
</tr>
<tr>
<td>Dolomite</td>
<td>0.64%</td>
<td>2.2%</td>
<td>5.5%</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.40%</td>
<td>1.5%</td>
<td>4.1%</td>
</tr>
</tbody>
</table>

CSLF and DOE-NETL Methodology

- Methods presented by CSLF (2007) and DOE (2007, 2008, 2010) are the same method (Gorecki et al., 2009)
- Any storage volume estimated with one method can be compared to the other, as long as the assumptions made are the same (Gorecki et al., 2009)


\[ V_{CO_2,DOE_E} = A * h * \phi * E_E \]
\[ V_{CO_2,CSLF_E} = A * h * \phi * (1 - S_{wirr}) * C_C \]
\[ E_E = C_C * (1 - S_{wirr}) \]
\[ V_{CO_2,DOE_E} = V_{CO_2,CSLF_E} \]
USGS Technically Accessible Storage Resource Estimate

- Stems from 2007 Energy Independence and Security Act (Public Law 110-140)
- The technically accessible storage resource is defined as the mass of CO\(_2\) that can be stored in the pore volume of the storage formation taking into account present-day geologic knowledge and engineering practice and experience.
- Open boundaries / regional to sub-basinal scale
- CO\(_2\) storage is divided into buoyant and residual trapping with classes based on permeability

\[ SF_{PV, USGS} = A_{SF} \times T_{PI} \times \phi_{PI} \]

<table>
<thead>
<tr>
<th>Injectivity Classification Section</th>
<th>Residual Trapping Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 1  permeability greater than 1 Darcy</td>
<td>Efficiency 1 5 7</td>
</tr>
<tr>
<td>Class 2  permeability between 0.001 Darcy to 1 Darcy</td>
<td>Efficiency 1 7 15</td>
</tr>
<tr>
<td>Class 3  permeability less than 1 mDarcy</td>
<td>Efficiency 0 0 7</td>
</tr>
</tbody>
</table>

Szulczewski et al. (2012) Migration-limited Capacity
Lifetime of carbon capture and storage as a climate-change mitigation technology

- **Migration-limited Capacity**: injected volume in which the CO$_2$ plume will reach the boundary of the aquifer and become completely trapped by residual and solubility trapping
- **Pressure-limited Capacity**: limitations due to injection rate
- Methodology considers **residual trapping**, in which zones of CO$_2$ become immobilized by capillary forces and **solubility trapping**, in which CO$_2$ dissolves into the groundwater at the basin scale / open and closed boundaries

\[ C_t = \rho_g L T W H \phi (1 - S_{wc})^2 / \varepsilon_t \]

- The major assumptions in the model are:
  - (1) the interface between the CO$_2$ and brine is sharp
  - (2) capillary pressure effects are negligible
  - (3) the flow is predominantly horizontal (Dupuit approximation)
  - (4) CO$_2$ leakage through the caprock is negligible
  - (5) the aquifer is homogeneous, isotropic, and incompressible
  - (6) the fluids are incompressible and their properties are constant
  - (7) during the dissolution of CO$_2$ into brine, the total fluid volume is conserved.

Zhou et al. (2008)
A method for quick assessment of CO$_2$ storage capacity in closed and semi-closed saline formations

- CO$_2$ injection into these systems will lead pressure buildup, because an additional volume of fluid needs to be stored.
- Injected CO$_2$ displaces an equivalent volume of native brine, which may either (1) be stored in the expanded pore space due to compression of the rock, (2) be stored in the expanded pore space in the seals, and 3) leakage of brine (closed boundaries).
- Provide CO$_2$ storage estimates at early stages of site selection and characterization, when (1) quick assessments of multiple sites may be needed and (2) site characterization data is sparse.

$$MCO_2(t_i) = (B_p + B_w) \Delta p(t_i) \rho V_f$$
$$= (B_p + B_w) \Delta p(t_i) \rho A b \phi$$

- maximum storage capacity for a given sustainable pressure buildup, $\Delta p_{\text{max}}$ (maximum pressure that the formation can sustain without geomechanical damage).
- Treated all parameters stochastically.

Description of Saline Formation Data Set

10 U.S. Saline Formations characterized by Szulczewski et al. (2012)
Mt. Simon, Black Warrior River, Frio, Madison, Navajo-Nugget, Morrison, Potomac, Fox Hills, Paluxy, St. Peter

Criteria:
(i) The depth must exceed 800 m so that CO$_2$ is stored efficiently as a high-density, supercritical fluid;
(ii) the aquifer and caprock must be laterally continuous over long distances;
(iii) there must be very few faults that could serve as leakage pathways

Assumption:
(i) cap rock is linear to ensure no structural trapping, (trapped at the top of an anticline or in a tilted fault block)

## Saline Storage Formations

**Example saline formation data set by Szulczewski et al. (2012)**

### Table S9: Parameters for Region a of the Frio Formation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Data Source</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual CO₂ saturation</td>
<td>$S_{rg}$</td>
<td>0.3</td>
<td>estimated</td>
<td>[40, 51]</td>
</tr>
<tr>
<td>Conrate water saturation</td>
<td>$S_{wc}$</td>
<td>0.4</td>
<td>estimated</td>
<td>[40, 51]</td>
</tr>
<tr>
<td>Endpoint relative permeability to CO₂</td>
<td>$k^{*}_{rg}$</td>
<td>0.6</td>
<td>estimated</td>
<td>[40, 51]</td>
</tr>
<tr>
<td>Coefficient of CO₂-saturated-brine flux</td>
<td>$\alpha$</td>
<td>0.01</td>
<td>estimated</td>
<td>[52, 53]</td>
</tr>
<tr>
<td>Compressibility (GPa⁻¹)</td>
<td>$c$</td>
<td>0.1</td>
<td>estimated</td>
<td>[30, Table C1]</td>
</tr>
<tr>
<td>Undrained Poisson ratio</td>
<td>$\nu$</td>
<td>0.3</td>
<td>estimated</td>
<td>[30, Table C1]</td>
</tr>
<tr>
<td>Geothermal gradient (°C/km)</td>
<td>$G_T$</td>
<td>30</td>
<td>aquifer data</td>
<td>[54, 55]</td>
</tr>
<tr>
<td>Surface temperature (°C)</td>
<td>$T_s$</td>
<td>20</td>
<td>aquifer data</td>
<td>[56]</td>
</tr>
<tr>
<td>Depth to top of aquifer (m)</td>
<td>$D$</td>
<td>1000</td>
<td>aquifer data</td>
<td>[47, Map c1fric]</td>
</tr>
<tr>
<td>Depth from aquifer to bedrock (m)</td>
<td>$B$</td>
<td>10000</td>
<td>aquifer data</td>
<td>[75]</td>
</tr>
<tr>
<td>Net aquifer thickness (m)</td>
<td>$H$</td>
<td>2000</td>
<td>aquifer data</td>
<td>[47, Map c3fric]</td>
</tr>
<tr>
<td>Length of model domain (km)</td>
<td>$L_T$</td>
<td>50</td>
<td>aquifer data</td>
<td>Fig. S10</td>
</tr>
<tr>
<td>Length of pressure domain (km)</td>
<td>$L_{pres}$</td>
<td>100</td>
<td>aquifer data</td>
<td>Fig. S10</td>
</tr>
<tr>
<td>Width of well array (km)</td>
<td>$W$</td>
<td>100</td>
<td>aquifer data</td>
<td>Fig. S10</td>
</tr>
<tr>
<td>Porosity</td>
<td>$\phi$</td>
<td>0.2</td>
<td>aquifer data</td>
<td>[76, Fig. 10]</td>
</tr>
<tr>
<td>Caprock slope (degrees)</td>
<td>$\theta$</td>
<td>2</td>
<td>calculated</td>
<td>[72, Fig. 2]</td>
</tr>
<tr>
<td>Darcy velocity (cm/yr)</td>
<td>$U$</td>
<td>10</td>
<td>calculated</td>
<td>[77]</td>
</tr>
<tr>
<td>Aquifer permeability (mD)</td>
<td>$k_{aq}$</td>
<td>400</td>
<td>aquifer data</td>
<td>[76, Fig. 8]</td>
</tr>
<tr>
<td>Mean vertical permeability (mD)</td>
<td>$k_{cvp}$</td>
<td>0.01</td>
<td>estimated</td>
<td>[36–38]</td>
</tr>
<tr>
<td>Lateral overburden permeability (mD)</td>
<td>$k_{e}$</td>
<td>200</td>
<td>aquifer data</td>
<td>Fig. S4</td>
</tr>
<tr>
<td>Vertical overburden permeability (mD)</td>
<td>$F_s$</td>
<td>0.02</td>
<td>calculated</td>
<td>Fig. S4</td>
</tr>
<tr>
<td>Salinity (g/L)</td>
<td>$S$</td>
<td>50</td>
<td>aquifer data</td>
<td>[78, Fig. 2A]</td>
</tr>
<tr>
<td>CO₂ solubility (volume fraction)</td>
<td>$\chi_v$</td>
<td>0.07</td>
<td>calculated</td>
<td>[25]</td>
</tr>
<tr>
<td>Brine density (kg/m³)</td>
<td>$\rho_w$</td>
<td>1000</td>
<td>calculated</td>
<td>[24]</td>
</tr>
<tr>
<td>CO₂ density (kg/m³)</td>
<td>$\rho_g$</td>
<td>500</td>
<td>calculated</td>
<td>[22]</td>
</tr>
<tr>
<td>Brine density change from diss. (kg/m³)</td>
<td>$\Delta \rho_d$</td>
<td>8</td>
<td>calculated</td>
<td>[28, 59]</td>
</tr>
<tr>
<td>Brine viscosity (mPa s)</td>
<td>$\mu_w$</td>
<td>0.8</td>
<td>calculated</td>
<td>[24]</td>
</tr>
<tr>
<td>CO₂ viscosity (mPa s)</td>
<td>$\mu_g$</td>
<td>0.04</td>
<td>calculated</td>
<td>[22]</td>
</tr>
<tr>
<td>Fracture pressure (MPa)</td>
<td>$P_{f,frac}$</td>
<td>20</td>
<td>calculated</td>
<td>Eq. S29,S28</td>
</tr>
</tbody>
</table>

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* We set the Darcy velocity to 10 cm/yr based on reported ranges for the velocity [77] and other deep saline aquifers.

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**Figure S9:** The Frio Formation is located on the east coast of Texas. It dips and thickens toward the coast. (a) Modified from [47, Map c1fric1]. (b) Modified from [47, Map c4fric].

**Figure S10:** We identify four boundaries that constrain the portion of the Frio Formation that is suitable for sequestration. Boundaries 1 and 3 correspond to the edges of available depth and thickness maps [47]. Boundary 2 corresponds to where the proportion of shale in the formation becomes greater than 80% [47, Map 5fric]. Boundary 4 corresponds to outcrops [47]. Within these boundaries, we identify three regions in which to apply our models (Regions a, b, and c).
Comparison of CO$_2$ Storage Methodologies

- Used select data and formations from Szulczewski, 2012: net aquifer thickness (H), length of trapping-model domain (L$_T$), width of well array (W), porosity ($\phi$), CO$_2$ density ($\rho_g$), connate water saturation ($S_{wc}$), aquifer permeability ($k_{aq}$), surface temperature ($T_s$), temperature gradient ($G_T$), depth to the top of the aquifer (D), brine density ($\rho_{w}$), and salinity (s).

- Estimated gross thickness by dividing the net thickness, by a net-to-gross thickness efficiency term [0.48 for clastics, 0.41 for dolomite, and 0.35 for limestone formations]

- Pore compressibility set to range between $1 \times 10^{-10}$ and $5 \times 10^{-10}$ Pa$^{-1}$.

- Brine compressibility directly calculated as described by Battistelli et al. 1997.

- Excluded formations that were less than 10,000 ppm TDS
Comparison of CO$_2$ Storage Methodologies

- **Apply uniform input parameters** for each method
  - Consistently applied inputs for length, width, porosity, and CO$_2$ density

- **Gross or net thickness** was applied as prescribed by the methodology

- Each methodology required the use of a **specific efficiency**
  - gauges the fraction of the accessible pore volume that will be occupied by the injected CO$_2$.
  - based on **lithology** or **rock permeability** class
  - calculated for each **individual formation**
  - **CO$_2$ trapping mechanisms**
    - **Residual** (Szulczewski et al. (2012), USGS: Brennan et al. (2010)
    - **Solubility** (Szulczewski et al. (2012)
Comparison of CO₂ Storage Methodologies

Mid CO₂ Storage Resource Potential

<table>
<thead>
<tr>
<th>Methodology</th>
<th>CO₂ Storage Resource (Gtonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOE-NETL: Altas I, II (2007, 2008) open</td>
<td>66.5 58.2 51.9 43.6 18.7 18.2 25.4 13.1 7.5 7.5 6.2 0.5 1.0</td>
</tr>
<tr>
<td>CSLF: Bachu et al. (2007) open</td>
<td>71.8 62.8 56.1 47.1 20.2 19.6 20.7 14.1 8.1 6.1 6.7 0.6 1.1</td>
</tr>
<tr>
<td>USGS: Brennan et al. (2010) open</td>
<td>95.6 83.6 74.7 62.7 26.9 26.1 26.9 18.8 13.3 10.7 11.1 2.6 1.4</td>
</tr>
<tr>
<td>DOE-NETL: Atlas III (2010) open</td>
<td>53.2 46.5 41.6 34.9 15.0 14.5 15.3 10.5 6.0 4.5 5.0 0.4 0.8</td>
</tr>
<tr>
<td>Szulczewski et al. (2012) migration-limited</td>
<td>10.0 88.0 18.0 17.0 8.6 12.0 6.6 14.0 5.1 5.3 4.0 1.5 1.6</td>
</tr>
<tr>
<td>Zhou et al. (2008) closed</td>
<td>16.9 15.1 8.7 5.5 2.8 2.5 8.3 1.8 3.5 3.5 3.0 0.1 0.3</td>
</tr>
</tbody>
</table>
# Comparison of CO₂ Storage Methodologies

<table>
<thead>
<tr>
<th>Methodology</th>
<th>CO₂ Storage Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOE-NETL: Altas I, II (2007, 2008) open</td>
<td>2.5% 2.5% 2.5% 2.5% 2.5% 2.5% 2.5% 2.5% 2.5% 2.5% 2.5% 2.5% 2.5% 2.5% 2.5% 2.5%</td>
</tr>
<tr>
<td>CSLF: Bachu et al. (2007) open</td>
<td>4.5% 4.5% 4.5% 4.5% 4.5% 4.5% 4.5% 4.5% 4.5% 4.5% 4.5% 4.5% 4.5% 4.5% 4.5% 4.5%</td>
</tr>
<tr>
<td>USGS: Brennan et al. (2010) open</td>
<td>7.0% 7.0% 7.0% 7.0% 7.0% 7.0% 7.0% 7.0% 7.0% 7.0% 7.0% 7.0% 7.0% 7.0% 7.0% 7.0%</td>
</tr>
<tr>
<td>DOE-NETL: Atlas III (2010) open</td>
<td>2.0% 2.0% 2.0% 2.0% 2.0% 2.0% 2.0% 2.0% 2.0% 2.0% 2.0% 2.0% 2.0% 2.0% 2.0% 2.0%</td>
</tr>
<tr>
<td>Szulczewski et al. (2012) migration-limited</td>
<td>1.3% 13.1% 3.0% 3.4% 2.3% 4.0% 5.7% 3.1% 9.3% 11.8% 5.9% 6.1% 5.6% 3.8% 24.8% 13.9%</td>
</tr>
<tr>
<td>Zhou et al. (2008) closed</td>
<td>0.6% 0.7% 0.4% 0.3% 0.3% 0.4% 0.3% 0.8% 0.3% 0.7% 1.2% 1.2% 1.2% 0.3% 0.7% 0.7%</td>
</tr>
</tbody>
</table>

*Efficiency is specific to each methodology and may not be directly comparable.
Comparison of CO₂ Storage Methodologies

General trends:

- All six methodologies fell within two standard deviations of the mean of an arithmetic averaging estimator for all 13 locations.
- The method by Zhou et al. (2008), typically, reports the lowest estimates.
- The method by USGS: Brennan et al. (2010), typically, reports the highest estimates.
- In most cases, the migration-limited estimates by Szulczewski et al. (2012) are similar to the closed estimates provided by Zhou et al. (2008) (Szulczweski et al (2012) pressure-limited estimates are directly comparable to Zhou et al. (2008)).

Summary:

- Applied several different resource estimation methodologies to uniform data set.
- As is typical for these types of estimates currently for carbon storage in saline fields, the data sets were very sparse.
- Open system methodologies gave median results that were well within the uncertainty bounds of the others.
  - High degree of confidence that the methodologies are reasonable and that the results can be used by decision-makers.
- Closed system estimates were consistently lower than those of the open system methodologies, but the estimated values from the closed system were also mostly well within the uncertainty bounds of the open system estimates.
Summary

- High-level assessments of potential CO\(_2\) storage reservoirs in the United States and Canada at the regional and national scale.
- Geologic formations:
  - oil and gas reservoirs
  - saline formations
  - unmineable coal seams
  - basalt formations
  - organic-rich shale basins
- Based on physically accessible pore volume without consideration of regulatory or economic constraints.
- Used for broad energy-related government policy and business decisions.

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Acknowledgments

• The authors would also like to thank John Litynski, Strategic Center for Coal, Carbon Storage, United States Department of Energy, National Energy Technology Laboratory; Stefan Bachu, CO₂ Storage Alberta Innovates – Technology Futures, Edmonton, AB, Canada; Sean Brennan, U.S. Geological Survey, Reston, Virginia; Ruben Juanes, Civil and Environmental Engineering and Center for Computational Engineering, Massachusetts Institute of Technology, Cambridge, MA; Michael Szulczewski, Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA; Quanlin Zhou, Lawrence Berkeley National Laboratory (LBNL), Earth Sciences Division, Berkeley, CA; Scott Frailey, Illinois State Geologic Survey, Midwest Geological Sequestration Consortium; and Charlie Gorecki, Energy & Environmental Research Center (EERC), University of North Dakota for reviewing calculations and helpful discussions.