Technical Economic and Regulatory Challenges Facing Large Scale Adoption of Carbon Geologic Sequestration

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Global CO\textsubscript{2} Cycle

CO\textsubscript{2} Cycle (billion tons per year, GT)

- Total Emissions: 800 GT annually
- Natural Sequestration: 788 GT
- Balance: 12 GT

- Atmospheric CO\textsubscript{2} levels rising since start of industrial era.
- Present concentrations of 400 ppm CO\textsubscript{2} close to 2050 target of 450 ppm.
C02 Abatement Targets

- With business as usual, CO₂ emissions by 2035 will have reached the threshold for limiting temperature rise to 2°C this century.

- Need to reduce emissions in the 100s-1000 GT range in this century to meet atmospheric CO₂ and temperature targets.
Geologic Sequestration Necessary to Meet Emission Targets

Preliminary Global CO2 Storage Capacity (Gtons)

- China 1,435
- US 2,150
- Japan 45
- Brazil 2,000
- India 225
- Africa 20
- Australia 740
- Europe 230
Challenges for Scaling Up CCS

• Carbon Capture and Storage Costs
• Inadequate Transportation Network
• Storage Uncertainties including Seismic Risk and Injectivity
• Regulatory and Legal Issues

U.S. Carbon Dioxide Emissions, By Source

- Electricity 37%
- Transportation 31%
- Industry 15%
- Residential & Commercial 10%
- Other (Non-Fossil Fuel Combustion) 6%

Carbon Capture Technologies

Post-combustion (PC)

Pre-combustion (IGCC)

Oxy Combustion

CO₂ Compression and Dehydration

Power & Heat

CO₂ Separation

CO₂

N₂

O₂

Coal

Air

Air/O₂

Coal

Gasification

Shift, Gas Cleanup + CO₂ Separation

H₂

Power & Heat

Steam

Air

CO₂

Air Separation

N₂

O₂

Coal

Air
Emissions Rate by Plant Type and Capacity

rubin, 2015

- Most coal-based plants have similar emission rates
- A typical 300 MW coal-based power plant emits ~ 2 Mtco₂/year
- Natural gas-based plants emit approximately half the CO₂ of coal-based plant
• For a typical 300 MW plant that emits 2 MtCO₂/year – annual abatement cost ~ $80M/yr
Carbon Capture and Storage Cost Components

- EOR credits ~ $15 - $40 per ton depending on oil price (Rubin, 2015)

Estimated from Rubin, 2015
Cost Mitigation by Enhanced Oil Recovery (EOR)

Affordable cost for EOR ~ 2% of oil price in $/bbl. At $100, = $36/tCO2, at $50 = $18.

- Large quantities of CO₂ can be used in US for EOR operations

- ~ 370 GT can be stored globally in association with EOR

<table>
<thead>
<tr>
<th>Region</th>
<th>CO₂ EOR Oil Recovery (Billions of barrels)</th>
<th>CO₂ Storage Capacity (Billions of metric tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Asia Pacific</td>
<td>47</td>
<td>13</td>
</tr>
<tr>
<td>2. Central &amp; South America</td>
<td>93</td>
<td>27</td>
</tr>
<tr>
<td>3. Europe</td>
<td>41</td>
<td>12</td>
</tr>
<tr>
<td>4. FSU</td>
<td>232</td>
<td>66</td>
</tr>
<tr>
<td>5. Middle East/North Africa</td>
<td>595</td>
<td>170</td>
</tr>
<tr>
<td>6. NA/Other</td>
<td>38</td>
<td>11</td>
</tr>
<tr>
<td>7. North America/U.S.</td>
<td>177</td>
<td>51</td>
</tr>
<tr>
<td>8. South Africa/Antarctica</td>
<td>74</td>
<td>21</td>
</tr>
<tr>
<td>Total</td>
<td>1,297</td>
<td>370</td>
</tr>
</tbody>
</table>
Average Cost of Construction for 300 MW Electric Plant

Cost ($Billion)

- Post-combustion Coal
- Natural Gas
- Pre-combustion Coal
- Oxy-combustion

Cost with capture

Cost without capture

modified from Rubin, 2015
Coal plants competitive even with capture and storage costs
How much does electricity cost?
Average national electricity prices in US cents/kWh (2011)

Data: average prices from 2011 converted at mean exchange rate for that year
Sources: IEA, EIA, national electricity boards, OANDA shrinkthatfootprint.com
Further Incentive for CSS Adoption and Lowering of Cost with Carbon Credits
Inadequate CO\textsubscript{2} Pipeline Network
Uncertainty in National Carbon Policy Affecting Coal Production

ANNUAL COAL PRODUCTION IN WEST VIRGINIA

MILLIONS OF SHORT TONS

SOURCE: ENERGY INFORMATION ADMINISTRATION
Uncertainty in Carbon Policy Causing Fiscal Distress for Coal Miners

- 26 coal mining companies have filed for bankruptcy protection in the past 5 years
Storage Risk – The Case of Kansas

- Kansas was assumed to lie in a seismically benign area
Earthquake Trends in Southern Kansas

- Large earthquakes (> M3.8) in past year associated with waste water injection in saline aquifer being considered for CO₂ injection

- EPA now requires seismic risk assessment at Class VI injection well sites
Seismic Trends and Implications for CSS

- Some abatement in seismicity following restrictions on injection rates and volumes in Kansas

Equivalent to 16 Mtons of CO₂ (~8 years of CO₂ emissions from a 300 MW electric power plant)
Earthquake Trends in Central and Eastern US

- Induced seismicity linked to waste disposal in saline aquifers being considered for CO₂ storage
Induced Seismicity - Physical Mechanisms

Subsurface Stress Field

Stresses on Fault Plane

Effect of Injection on Fault Stability
### Relationship Between Earthquake Magnitude and Infrastructure Damage

<table>
<thead>
<tr>
<th>Richter Magnitudes</th>
<th>Description</th>
<th>Earthquake Effects</th>
<th>Frequency of Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 2.0</td>
<td>Micro</td>
<td>Micro-earthquakes, not felt.</td>
<td>About 8,000 per day</td>
</tr>
<tr>
<td>2.0-2.9</td>
<td>Minor</td>
<td>Generally not felt, but recorded.</td>
<td>About 1,000 per day</td>
</tr>
<tr>
<td>3.0-3.9</td>
<td>Minor</td>
<td>Often felt, but rarely causes damage.</td>
<td>49,000 per year (est.)</td>
</tr>
<tr>
<td>4.0-4.9</td>
<td>Light</td>
<td>Noticeable shaking of indoor items, rattling noises. Significant damage unlikely.</td>
<td>6,200 per year (est.)</td>
</tr>
<tr>
<td>5.0-5.9</td>
<td>Moderate</td>
<td>Can cause major damage to poorly constructed buildings over small regions. At most slight damage to well-designed buildings.</td>
<td>800 per year</td>
</tr>
<tr>
<td>6.0-6.9</td>
<td>Strong</td>
<td>Can be destructive in areas up to about 160 kilometres (100 mi) across in populated areas.</td>
<td>120 per year</td>
</tr>
<tr>
<td>7.0-7.9</td>
<td>Major</td>
<td>Can cause serious damage over larger areas.</td>
<td>18 per year</td>
</tr>
<tr>
<td>8.0-8.9</td>
<td>Great</td>
<td>Can cause serious damage in areas several hundred miles across.</td>
<td>1 per year</td>
</tr>
<tr>
<td>9.0-9.9</td>
<td>Great</td>
<td>Devastating in areas several thousand miles across.</td>
<td>1 per 20 years</td>
</tr>
<tr>
<td>10.0+</td>
<td>Epic</td>
<td>Never recorded; see below for equivalent seismic energy yield.</td>
<td>Extremely rare (Unknown)</td>
</tr>
</tbody>
</table>
Faults less than 3.5 km (2.3 mi) long are not likely to cause severe damage even if they slip. Need to map large faults.
Inadequate Fault Mapping

- Faults in naturally dormant areas not adequately mapped.
Wellington CO$_2$ Sequestration and EOR Site

- Approximately 26,000 tons to be injected in the Arbuckle aquifer for CO$_2$ sequestration and 26,000 tons in the overlying Mississippian reservoir for EOR.

- Extensive data acquisition required to identify faults and assess seismic risk.
Regulatory Issues

• US EPA Class VI permit required to inject:
  
  > Goals
  
  a) prevent CO₂ migration into Underground Sources of Drinking Water (USDW) – TDS > 10,000 ppm (substantially higher than drinking water limit of 500 ppm)
  
b) protect caprock Integrity
  
c) prevent earthquakes
  
  > Expensive multi-year process requiring deep drilling, testing, and analysis to characterize the formation and perform corrective action on wells within the EPA Area of Review (AoR)
  
  > 50 years post-injection monitoring period
  
  > Between $8 - $70 million financial assurance (bond/insurance, @ 5% cost could be as high as $3.5 million annually)
  
  > Guidelines required for defining aquifer – 2 GPD/day yield threshold for well quite restrictive
  
  > Fracture gradient restriction fairly stringent
Maximum Allowable (Fracture-Based) Increase in Pore Pressure (psi)
Simulated increase in pore pressures due to injection of 12 million tons/year of CO2 over a 50 year period at 10 targeted sites in Kansas

Increase in pore pressure (psi) at 50 years

Williams, Gerlach, Fazelalavi, Doveton, et al., 2014

- Pressures greater than 700 psi can occur in the injection zone
Maximum Allowable Fracture-Based Increase in Pore Pressure

- May not be feasible to inject in large areas due to fracture gradient requirement even in the presence of tight caprock and confining layers within the injection zone.
Effect of Stratification on Plume Migration and Pressure Distribution At Wellington CO2 Storage Site

Entry pressure in caprock is 955 psi

- CO\textsubscript{2} to remain deep in the injection zone. Negligible pressure increase at base of caprock

Holubnyack, Rush, Fazelalavi (KGS)
Simulated Sequestered Volumes of CO$_2$ in Kansas

- Total sequestered volume over 50 year period ~ 0.65 GT (almost a decade of CO2 emissions in Kansas).
Other Outstanding Issues Hindering CSS Adoption

- Lack of formal national/global carbon emissions policy
- Creation of an industry-financed trust fund
- Adoption of substantive or procedural limitations on claims
- Laws and regulations regarding ownership of pore space and long-term stewardship
- Standards to account for cross-border movement of stored CO₂
- Negative public perception