Carbon Capture and Sequestration (CCS) 101

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Global Challenges – Global Solutions – Global Opportunities
What is CCS?

• **CCS**: Carbon Capture and Sequestration
  – Also, called Carbon Capture and Storage
  – Carbon Capture and Geological Storage (CCGS)

Sequestration: The state of being alone or being kept apart from others. (Merriam Webster Dictionary)
Carbon Dioxide Capture and Sequestration Involves 4 Steps

Capture ➔ Compression ➔ Pipeline Transport ➔ Geological Sequestration
Carbon Capture and Sequestration 101: Objectives

- Familiarity with Concepts and Terminology
- The Case for Carbon Capture and Sequestration
- Technology Overview
  - Capture
  - Transportation
  - Sequestration
- Risks of CCS
- Global and N. American Potential for CCS
- Costs of CCS
- Institutional Incentive and Barriers
Carbon dioxide emissions have risen dramatically over the past two hundred years…

…leading to the buildup of carbon dioxide in the atmosphere, global warming, and ocean acidification.

We need to reduce CO$_2$ emissions dramatically, beginning now.
Why CCS? Decreasing Reliance on Fossil Fuels Will Be Challenging

- 85% of U.S. energy supply from fossil fuels
- 80% of U.S. energy supply projected by 2030
- Reductions of CO$_2$ and other greenhouse gases of 50 to 80% are needed by 2050
- Low carbon emission electricity options
  - Renewable energy (sun and wind)
  - Nuclear power
- Growth of these is unlikely to be fast enough to achieve needed emission reductions

Global Energy Consumption (EJ)

EJ = 10$^{18}$ Joules

Source: BP World Energy Review
Why CCS? We Are Not Running Out of Fossil Fuels.

Stored Energy Resources

Ratio of Resources to Annual Human Energy Use

- Geothermal Energy*
- Deuterium–tritium (from Li)
- Uranium
- Thorium
- Coal
- Gas Hydrates
- Oil
- Gas

CCS Can Reduce Emissions from Many Sources

CCS is applicable to the 60% of CO₂ emissions which come from stationary sources such as power plants, cement plants and refineries.

7,400 sources greater than 0.1 Mt/yr
CCS Is Expected to Contribute About 20% to Needed CO₂ Emission Reduction
Technology Overview

Capture → Compression → Pipeline Transport → Geological Sequestration
Option 1. Post-Combustion Capture

CO₂ is captured after fuel has been burned

Image Courtesy of ZEP
Post-Combustion Capture

Treated Flue Gas (~90% capture) (~1% CO₂ + N₂)

Rich Solvent

Lean Solvent

Regenerated Solvent

Flue Gas (5-15% CO₂ + N₂)

CO₂

Steam

Huaneng Group Post Combustion Capture Pilot, Beijing, China, 3000 t/yr
Option 2. Oxy-Combustion

CO₂ is captured during fuel combustion

Image Courtesy of ZEP
Option 3. Pre-Combustion Capture

CO₂ is captured before fuel is burned

Image Courtesy of ZEP
## Comparison of Capture Options

<table>
<thead>
<tr>
<th>Technology</th>
<th>Advantages</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-Combustion</td>
<td>• Mature technology</td>
<td>• High energy penalty (~30%)</td>
</tr>
<tr>
<td></td>
<td>• Standard retrofit</td>
<td>• High cost for capture</td>
</tr>
<tr>
<td>Pre-Combustion (IGCC)</td>
<td>• Lower costs than post-combustion</td>
<td>• Complex chemical process</td>
</tr>
<tr>
<td></td>
<td>• Lower energy penalties (10-15%)</td>
<td>• Repowering</td>
</tr>
<tr>
<td></td>
<td>• H₂ production</td>
<td>• Large capital investment</td>
</tr>
<tr>
<td>Oxygen-Combustion</td>
<td>• Avoid complex post-combustion separation</td>
<td>• Oxygen separation</td>
</tr>
<tr>
<td></td>
<td>• Potentially higher generation efficiencies</td>
<td>• Repowering</td>
</tr>
</tbody>
</table>
Technology Overview

- Compression of CO₂ to a liquid state (about 100 bars)
  - Compression is a mature technology
- Transport of liquid CO₂ in pipelines
  - Pipeline transport is a mature technology with over 2,000 miles of pipelines in the U.S.
Technology Overview

[Diagram showing the process of carbon capture, compression, pipeline transport, and geological sequestration.]
What Types of Rock Formations are Suitable for Geological Storage?

*Rocks in deep sedimentary basins are suitable for CO$_2$ storage.*

- **Example of a sedimentary basin with alternating layers of sandstone and shale.**
- **Map showing world-wide sedimentary basins**
- **Northern California Sedimentary Basin**
- **Sandstone**
Options for Geological Storage

Overview of Geological Storage Options

1. Depleted oil and gas reservoirs
2. Use of CO₂ in enhanced oil and gas recovery
3. Deep saline formations - (a) offshore (b) onshore
4. Use of CO₂ in enhanced coal bed methane recovery
Basic Concept of Geological Sequestration of CO$_2$

- Injected at depths of 1 km or deeper into rocks with tiny pore spaces
- Primary trapping
  - Beneath seals of low permeability rocks

Courtesy of John Bradshaw

Image courtesy of ISGS and MGSC
X-ray Micro-tomography at the Advanced Light Source

Micro-tomography Beamline

Image of Rock with CO$_2$

- CO$_2$
- Water
- Mineral grain

2 mm
“Observations from engineered and natural analogues as well as models suggest that the fraction retained in appropriately selected and managed geological reservoirs is very likely* to exceed 99% over 100 years and is likely** to exceed 99% over 1,000 years.”

“With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods to stop or control CO₂ releases if they arise, the local health, safety and environment risks of geological storage would be comparable to risks of current activities such as natural gas storage, EOR, and deep underground disposal of acid gas.”

* "Very likely" is a probability between 90 and 99%.
** Likely is a probability between 66 and 90%.
Evidence to Support these Conclusions

- Natural geological analogs
  - Oil and gas reservoirs
  - CO₂ reservoirs
- Performance of industrial analogs
  - 40 years experience with CO₂ EOR
  - 100 years experience with natural gas storage
  - Acid gas disposal
- 30+ years of cumulative performance of actual CO₂ storage projects
  - Sleipner, off-shore Norway, 1996
  - Weyburn, Canada, 2000
  - In Salah, Algeria, 2004
  - Snovhit, Norway, 2008

~40 Mt/yr are injected for CO₂-EOR
Natural Gas Storage

- Seasonal storage to meet winter demands for natural gas
- Storage formations
  - Depleted oil and gas reservoirs
  - Aquifers
  - Caverns
Sleipner Project, North Sea

- 1996 to present
- 1 Mt CO$_2$ injection/yr
- Seismic monitoring

Courtesy Statoil
Seismic Monitoring Data from Sleipner

From Chadwick et al., GHGT-9, 2008.
Plume and topmost layer 2001 - 2006

From Andy Chadwick, BGS, 2010
Seal Rocks and Trapping Mechanisms

- Seal rock geology
  - Shale
  - Clay
  - Carbonates

- Two trapping mechanisms
  - Permeability barriers to CO$_2$ migration
  - Capillary barriers to CO$_2$ migration
Secondary Trapping Mechanisms Increase Over Time

- **Solubility trapping**
  - $\text{CO}_2$ dissolves in water
- **Residual gas trapping**
  - $\text{CO}_2$ is trapped by capillary forces
- **Mineral trapping**
  - $\text{CO}_2$ converts to solid minerals
- **Adsorption trapping**
  - $\text{CO}_2$ adsorbs to coal
Risk Management

- Injection begins
- Injection stops
- 2 x injection period
- 3 x injection period
- n x injection period

Health Safety and Environmental Risk

- Site selection
- Active and abandoned well completions
- Storage engineering
- Pressure recovery
- Secondary trapping mechanisms
- Confidence in predictive models

Acceptable Risk

Monitor & Model

- Calibrate & Validate Models
- Calibrate & Validate Models
Potential Consequences

1. Worker safety
2. Groundwater quality degradation
3. Resource damage
4. Ecosystem degradation
5. Public safety
6. Structural damage
7. Release to atmosphere

Potential Release Pathways

- Well leakage (injection and abandoned wells)
- Poor site characterization (undetected faults)
- Excessive pressure buildup damages seal
Key Elements of a Geological Storage Safety and Security Strategy

“With appropriate site selection informed by available subsurface information, a monitoring program to detect problems, a regulatory system, and the appropriate use of remediation methods...”

Long Term Stewardship and Financial Responsibility

Regulatory Oversight

Remediation

Monitoring

Safe Operations

Storage Engineering

Site Characterization and Selection

Fundamental Storage and Leakage Mechanisms

“... risks similar to existing activities such as natural gas storage and EOR.”

“... the fraction retained is likely to exceed 99% over 1,000 years.”

IPCC, 2005
Oil and gas reservoirs could potentially store about 60 years of current emissions from power generation.
Unminable coal formations could potentially store about 80 years of current emissions from power generation.

CO₂ Resource Estimates by Regional Carbon Sequestration Partnership for Unmineable Coal Seams

<table>
<thead>
<tr>
<th>RCSP</th>
<th>Low Billion Metric Tons</th>
<th>High Billion Metric Tons</th>
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<tbody>
<tr>
<td>BSCSP</td>
<td>12.1</td>
<td>13.3</td>
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<tr>
<td>MGSC</td>
<td>1.7</td>
<td>1.8</td>
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<tr>
<td>MRCSP</td>
<td>0.8</td>
<td>0.9</td>
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<tr>
<td>PCORP</td>
<td>10.7</td>
<td>11.8</td>
</tr>
<tr>
<td>SECARB</td>
<td>57.8</td>
<td>63.7</td>
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<tr>
<td>SWP</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>WESTCARB</td>
<td>86.8</td>
<td>95.7</td>
</tr>
<tr>
<td>TOTAL</td>
<td>170.6</td>
<td>188.0</td>
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</table>

TOTAL: 197.3 Billion Metric Tons
Saline aquifers could potentially store more than 1,000 years of current emissions from power production.
# Global Sequestration Capacity Estimates

<table>
<thead>
<tr>
<th>Region</th>
<th>Estimated Storage Capacity (billion tons of CO2)</th>
<th>Source</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Depleted Oil and Gas Reservoirs</td>
<td>Saline Aquifers</td>
<td>Coal Seams</td>
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<tr>
<td>North America</td>
<td>143</td>
<td>3600-13000</td>
<td>187-217</td>
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<tr>
<td>Latin America</td>
<td>89</td>
<td>30.3</td>
<td>2</td>
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<tr>
<td>Brazil</td>
<td>NA</td>
<td>2000</td>
<td>0.2</td>
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<tr>
<td>Australia</td>
<td>19.6</td>
<td>28.1</td>
<td>11.3</td>
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<tr>
<td>Japan</td>
<td>0</td>
<td>1.9-146</td>
<td>0.1</td>
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<tr>
<td>Centrally Planned Asia and China (CPA)</td>
<td>9.7-21</td>
<td>110-360</td>
<td>10</td>
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<tr>
<td>Other Pacific Asia (PAS)</td>
<td>56-188</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>South Asia (SAS)</td>
<td>6.5-7.4</td>
<td>NA</td>
<td>0.36-0.39</td>
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<td>Former Soviet Union (FSU)</td>
<td>177</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>Subsaharan Africa</td>
<td>36.6</td>
<td>34.6</td>
<td>7.6</td>
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<td>Middle East &amp; North Africa</td>
<td>439.5</td>
<td>9.7</td>
<td>0</td>
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<td>Europe</td>
<td>20.22-30</td>
<td>95.72-350</td>
<td>1.08-1.5</td>
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<td>World</td>
<td>996 - 1,150</td>
<td>5,900 - 16,000</td>
<td>210 - 240</td>
</tr>
</tbody>
</table>

From KM13 GEA, 2010.
Global Distribution of Commercial, Pilot and Demonstration Projects
Cost of CCS

- Complex to assess costs, depending on baseline, technology choices, site specific considerations
- Increase the cost of electricity generation by 50 to 100%

Distribution of costs for a typical CCS project.
None is likely to be a show stopper, but all require effort to resolve.
Maturity of CCS Technology

• Are we ready for CCS?

- **Oil and gas reservoirs**
  - State-of-the-art is well developed, scientific understanding is excellent and engineering methods are mature

- **Saline aquifers**
  - Sufficient knowledge is available but practical experience is lacking, economics may be sub-optimal, scientific understanding is good

- **Coalbeds**
  - Demonstration projects are needed to advance the state-of-the-art for commercial scale projects, scientific understanding is limited

- Pilot projects are needed to provide proof-of-concept, scientific understanding is immature
Concluding Remarks

- CCS is an important part of solving the global warming problem
- Progress on CCS proceeding on all fronts
  - Industrial-scale projects
  - Demonstration plants
  - Research and development
- Technology is sufficiently mature for commercial projects with CO$_2$-EOR and for large scale demonstration projects in saline aquifers
- Research is needed to support deployment at scale
  - Capture: Lower the cost and increase reliability
  - Sequestration: Increase confidence in storage permanence
- Institutional issues and incentives need to be addressed to support widespread deployment
Additional Reading and Resources