The Outlook for CO₂ Capture and Storage
And Its Role in a Low-Carbon Energy Future

Edward S. Rubin
Department of Engineering and Public Policy
Department of Mechanical Engineering
Carnegie Mellon University
Pittsburgh, Pennsylvania
Guest Lecture
19-656: CO₂ Capture and Sequestration
Carnegie Mellon University
February 6, 2014

Outline of Talk

• The problem of climate change
• Why the interest in CCS?
• The good news
• The not-so-good news
• Future outlook

The problem of global climate change

Major Greenhouse Gases (GHGs) Emitted from Human Activities

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Common Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
<td>Fossil fuel combustion, forest clearing, cement production, etc.</td>
</tr>
<tr>
<td>CH₄</td>
<td>Methane</td>
<td>Landfills, production and distribution of natural gas &amp; petroleum, fermentation from the digestive system of livestock, rice cultivation, fossil fuel combustion, etc.</td>
</tr>
<tr>
<td>N₂O</td>
<td>Nitrous Oxide</td>
<td>Fossil fuel combustion, fertilizers, nylon production, manure, etc.</td>
</tr>
<tr>
<td>HFCs</td>
<td>Hydrofluorocarbons</td>
<td>Refrigeration gases, aluminum smelting, semiconductor manufacturing, etc.</td>
</tr>
<tr>
<td>PFCs</td>
<td>Perfluorocarbons</td>
<td>Aluminum production, semiconductor industry, etc.</td>
</tr>
<tr>
<td>SF₆</td>
<td>Sulfur Hexafluoride</td>
<td>Electrical transmissions and distribution systems, circuit breakers, magnesium production, etc.</td>
</tr>
</tbody>
</table>

Unlike “conventional” air pollutants, GHGs—once emitted—are not easily removed. Most remain in the atmosphere for centuries.
Global GHG Emissions Have Been Increasing Rapidly

Continued increases are projected under “business as usual”

Atmospheric GHG Levels

- Greenhouse gas (GHG) concentrations in the atmosphere have been increasing rapidly as a result of human activities

Greenhouse Gases Trap Heat

Predicted Temperature Changes for a Doubling of Atmospheric CO₂ Concentration
Impacts of climate change increase at higher global temperatures

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Frequency</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>WATER</td>
<td>Increased water availability in some regions and drought in others.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Decreasing water availability due to increasing drought and floods.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increased number of people affected by floods and drought.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>Frequency</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biodiversity loss</td>
<td>Decreasing species diversity.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reduced forest cover.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increasing desertification</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Food</th>
<th>Frequency</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food prices rising</td>
<td>Decreasing food availability.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increase in hunger and malnutrition.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Coasts</th>
<th>Frequency</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased coastal flooding and erosion</td>
<td>Increased coastal flooding and erosion.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Loss of coastal wetlands.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Health</th>
<th>Frequency</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased mortality and morbidity from heat waves, floods, and storms.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increased incidence of vector-borne diseases.</td>
<td></td>
</tr>
</tbody>
</table>

More extreme events are expected as atmospheric concentration rises.

The Climate Policy Driver

- 1992 U.N. Framework Convention on Climate Change called for “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”

*192 countries are parties to the convention

Implication of Stabilization

- Because of their long atmospheric lifetimes (typically measured in centuries), stabilizing current GHG emissions is not sufficient to stabilize atmospheric concentrations
- Global emissions must be reduced significantly, no matter what stabilization target is selected!

Analogy: To stabilize the water level in a slow-draining tub, the open faucets must be tightened to a trickle.
Mitigating Climate Change Requires Large Emission Reductions

The most recent IPCC assessment indicates a need for large reductions by 2050 to avoid serious impacts (>2°C rise)

<table>
<thead>
<tr>
<th>Required change in global GHG emissions from 2000 to 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>-50% to -85%</td>
</tr>
</tbody>
</table>

Source: IPCC, 2007

This conclusion was affirmed in the recent (2010) report of the U.S. National Academies: "America’s Climate Choices"

Focus on CO₂ from Energy Use — the Dominant Greenhouse Gas

U.S. Greenhouse Gas Emissions weighted by 100-yr Global Warming Potential (GWP)

- CO₂: 7.4%
- CH₄: 6.5%
- N₂O: 2.2%
- Others: 83.9%

Total in 2005 = 7.26 Gt CO₂ equiv

Source: USEPA, 2007

Trend in World Energy Use

~85% of world energy is from fossil fuels

Energy for electricity generation and vehicles are the major sources of CO₂

Source: BP, 2011

Why the interest in CCS?

(carbon capture and storage, or sequestration)
Options to Mitigate CO₂ Emissions

- Reduce the demand for energy used in buildings, transportation, and industrial activities
- Improve the efficiency of energy conversion and utilization, so less fuel is needed to meet demands
- Produce and use alternative energy sources with low or no GHG emissions
- Capture and sequestration CO₂ at large industrial sources to prevent its release to the atmosphere

Schematic of a CCS System

Motivation for CCS

- CCS is the ONLY way to get large CO₂ reductions from continued use of fossil fuels—a potential bridging strategy to a sustainable energy future
- CCS can also help decarbonize the transportation sector (via low-carbon electricity and hydrogen from fossil fuels)

What It Takes to Reach GHG Goals

Least-cost U.S. energy mix in 2050 for a GHG policy scenario according to five energy models. All indicate that major changes in the energy system are needed.

CCS PLAYS A MAJOR ROLE (for coal, gas, and biomass)
Cost-Effective Global Strategies Also Require CCS in the Portfolio

Models show increasing need for CCS as stabilization goal tightens

Without CCS the cost of stabilization increases sharply

Without CCS the cost of stabilization increases sharply

The Good News

CCS Technology

• Is real
• It works
• It is effective
• It is commercially available

Applications of CO₂ Capture

Gas-fired power plant
Coal-fired power plant
Hy production plant
CO₂ Pipelines in the Western U.S.

> 3000 miles of pipeline
~50 MtCO₂/yr transported

Captured CO₂ Stored in a Deep Saline Formation

Sleipner Project (Norway)

Captured CO₂ Stored in a Depleted Gas Formation

In Salah /Krechba (Algeria)

Geological Formations in North America

Oil & Gas Fields
Deep Saline Formations
Captured CO₂ Stored with Enhanced Oil Recovery (EOR)

Weyburn Field, Canada

Dakota Coal Gasification Plant, ND

Sources: IEAGHG; NRDC; USDOE

E.S. Rubin, Carnegie Mellon

CCS at a Coal-Fired Power Plant
(Pilot plant with storage in a deep saline formation)

20 MW pilot plant at AEP’s Mountaineer Power Plant
(West Virginia)

E.S. Rubin, Carnegie Mellon

Current CCS Technology

- Is relatively expensive at present
- Not yet proven at full-scale power plants
- Some remaining legal and regulatory issues
- Uncertain public acceptance in some areas
- Few if any incentives to deploy CCS

The Not-So-Good News
Key Barriers to CCS Deployment

- Policy
- Policy
- Policy

Without a policy requirement or incentive there is little or no reason to deploy CCS.

Strong Interactions Between Policy and Other Key Factors

- Policy Actions
- Public Acceptance
- CCS Tech. & Cost
- Legal & Reg. Issues

These interactions depend strongly on local and national settings.

What If We Could Make it Cheaper?

Measures of CCS Cost:

- Increased cost of electricity
- Cost of CO₂ avoided
- Cost of CO₂ captured
- Capital cost
- Dispatch (variable) cost

Cost of CCS for New Coal-Based Plants Using Current Technology

Increase in levelized cost for 90% capture

<table>
<thead>
<tr>
<th>Incremental Cost of CCS, relative to same plant type without CCS (based on bituminous coals)</th>
<th>Supercritical Pulverized Coal Plant</th>
<th>Integrated Gasification Combined Cycle Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Increases in capital cost ($/kW) and generation cost ($/kWh)</td>
<td>~ 60–80%</td>
<td>~ 30–50%</td>
</tr>
</tbody>
</table>

- Capture accounts for most (~80%) of the total cost
- Retrofit of existing plants typically has a higher cost
- Added cost to consumers will be much smaller (reflecting the CCS capacity in the generation mix at any given time)
### CCS Cost for New NGCC Plants (Current Technology)

<table>
<thead>
<tr>
<th>Cost Measure</th>
<th>New NGCC Cost Increase with CCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Increase in generation cost ($/kWh) (relative to NGCC w/o CCS)</td>
<td>~30–45%</td>
</tr>
<tr>
<td>Cost of CO₂ Avoided:</td>
<td></td>
</tr>
<tr>
<td>Relative to NGCC:</td>
<td>~$100/ton CO₂</td>
</tr>
<tr>
<td>Relative to SCPC:</td>
<td>~$40/ton CO₂</td>
</tr>
</tbody>
</table>

Increase in levelized cost for 90% capture.

E.S. Rubin, Carnegie Mellon

### Definition of Key Costs

- Cost of CO₂ Avoided ($/ton CO₂ avoided)
  \[ \frac{(\$/MWh)_{\text{CS}} - (\$/MWh)_{\text{reference}}}{(CO₂/MWh)_{\text{eff}} - (CO₂/MWh)_{\text{CS}}} \]

- Cost of Electricity Generation ($/MWh)
  \[ \frac{(TCC)(FCF) + FOM}{(CF)(8760)(MW)} + VOM + (HR)(FC) \]

*Many factors influence the cost of CCS*

E.S. Rubin, Carnegie Mellon

### Ten Ways to Reduce CCS Cost

10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel price
7. Assume EOR credits for CO₂ storage
6. Omit certain capital costs
5. Report $/ton CO₂ based on short tons
4. Assume long plant lifetime
3. Assume low interest rate (discount rate)
2. Assume high plant utilization (capacity factor)
1. Assume *all of the above*!

... and we have not yet considered the CCS technology!

E.S. Rubin, Carnegie Mellon

### Future Outlook
**Large-Scale Demonstrations**
(Planned projects in the U.S. as of December 2013)

**R&D Programs Seek to Develop Lower-Cost Technologies**

**Most New Capture Concepts Are Far from Commercial Availability**

**Typical Cost Trend for a New Technology**
Two Approaches to Estimating Future Technology Costs

- **Method 1**: Engineering-Economic Analysis
  - A “bottom up” approach based on engineering process models, informed by judgments regarding potential improvements in key process parameters

- **Method 2**: Use of Historical Experience Curves
  - A “top down” approach based on applications of mathematical “learning curves” or “experience curves” that reflect historical trends for analogous technologies or systems

IECM: A Tool for Analyzing Power Plant Design Options

- A desktop/laptop computer simulation model developed for DOE/NETL
- Provides systematic estimates of performance, emissions, costs and uncertainties for preliminary design of:
  - PC, IGCC and NGCC plants
  - All flue/fuel gas treatment systems
  - CO₂ capture and storage options (pre- and post-combustion, oxy-combustion; transport, storage)
- Free and publicly available at: [www.iecm-online.com](http://www.iecm-online.com)

Estimated Cost of Two Advanced CO₂ Capture Systems

- **Sweep-based Membrane System**
  - Membrane CO₂ Permeance (gpm)
  - Substantial reductions seen in the cost of doing the same job at different points in time for the same power plant and fuel specifications

- **Chemical Looping Combustion System**
  - Cost of CO₂ Avoided ($/mt CO₂)

Historical Experience Curves for FGD and SCR Capital Costs

- Substantial reductions seen in the cost of doing the same job at different points in time for the same power plant and fuel specifications

- **Integrated Environmental Control Model**
  - Cost reductions of ~12% per doubling of installed capacity (~50% reduction in 20 years)
Application of Experience Curves to Future CCS Costs

(Percents cost reduction, 2001–2050, based on energy-economic modeling)*

<table>
<thead>
<tr>
<th>Power Plant System</th>
<th>Reduction in Cost of Electricity ($/MWh)</th>
<th>Reduction in Mitigation Cost ($/tCO₂ avoided)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGCC – CCS</td>
<td>12% – 40%</td>
<td>13% – 60%</td>
</tr>
<tr>
<td>IGCC – CCS</td>
<td>22% – 52%</td>
<td>19% – 58%</td>
</tr>
<tr>
<td>PC – CCS</td>
<td>14% – 44%</td>
<td>19% – 62%</td>
</tr>
</tbody>
</table>

* Range based on low and high global carbon price scenarios.

Source: van der Brink et al, 2010

Conclusions from CCS Cost Studies

- There is significant technical potential to reduce the cost of CCS for power plants and other industrial applications

  but ...

- Realization of that potential will require significant commercial deployment of CCS together with sustained R&D

Will CCS Save the Day?

- Very likely to soon see several large-scale demos of CCS, with continued R&D support; but ...

- Widespread use will require strong policy drivers that create markets for CCS

  WATCH THIS SPACE FOR UPDATES

Thank You

rubin@cmu.edu