The Cost of CO₂ Capture and Storage

Edward S. Rubin¹ and John Davison²

¹Carnegie Mellon University, Pittsburgh, PA, USA
²IEA Greenhouse Gas Programme, Cheltenham, UK

2nd Int’l. Conference on Clean Coal Technologies for Our Future
Castiadas (Cagliari), Sardinia, Italy
May 11, 2005

Motivating Questions

• What is the status of technologies for CO₂ capture and storage (CCS)?
• What is the current cost of CCS, and what are the factors that most influence cost?
• What is the impact of CCS on other environmental emissions and plant-level resource requirements?
• What is the outlook for future improvements that reduce CCS costs and impacts?
Schematic of a Typical CCS System

Coal or Natural Gas

Air or Oxygen

Energy Conversion Process

Useful Products
(Electricity, Fuels, Chemicals, Hydrogen)

CO₂ Capture

- Post-combustion
- Pre-combustion
- Oxyfuel combustion

CO₂ Transport

- Pipeline
- Tanker

CO₂ Storage (Sequestration)

- Depl. oil/gas fields
- Saline reservoirs
- Unmineable coal seams
- Ocean
- Mineralization

CO₂ Capture at a Coal-Fired Power Plant
(Shady Point, Oklahoma)

Source: ABB Lummus

E.S. Rubin, Carnegie Mellon
CO$_2$ Capture for H$_2$ Production from Coke Gasification
Farmland Industries, Coffeyville, Kansas

Existing CO$_2$ Pipelines for Enhanced Oil Recovery (EOR)
Weyburn CO$_2$ Pipeline & Storage Project
Geological Storage of CO$_2$ with Enhanced Oil Recovery

Geologic Sequestration of CO$_2$
(Sleipner Gas Field, North Sea, Norway)
### Status of CCS Technologies

- Technology for each major component of a CCS system (capture, transport, storage) can be found in commercial applications today, mainly in the petroleum and petrochemical process industries.
- CO₂ capture also has been applied to flue gas streams from several coal-fired and gas-fired boilers, but at much smaller sizes than a modern power plant.
- The integration of capture, transport and storage has been demonstrated, but not yet at an electric power plant.
- R&D programs are underway worldwide to develop improved, lower-cost options for CO₂ capture.

### Leading Candidates for CCS

- Fossil fuel power plants
  - Natural gas combined cycle (NGCC)
  - Pulverized coal combustion (PC)
  - Integrated coal gasification combined cycle (IGCC)
- Other large industrial sources of CO₂, e.g.,
  - Refineries and petrochemical plants
  - Hydrogen production plants
  - Pulp and paper plants
  - Etc.

*Main focus on power plants as the largest source of CO₂*
What Does It Cost?

Many Factors Affect Reported Costs of CO₂ Capture & Storage

- Choice of CCS Technology
- Process Design and Operating Variables
- Economic and Financial Parameters
- Choice of System Boundaries; e.g.,
  - One facility vs. multi-plant system (regional, national, global)
  - GHG gases considered (CO₂ only vs. all GHGs)
  - Power plant only vs. partial or complete life cycle
- Time Frame of Interest
  - Current technology vs. future (improved) systems
  - Consideration of technological “learning”
Different Measures of CCS Cost
Often Adds to the Confusion

- Cost per Unit of Product (e.g., $/MWh)
- Cost of CO₂ Avoided ($/ton CO₂ avoided)
- Cost of CO₂ Captured ($/ton CO₂ captured)
- Cost of CO₂ Reduced ($/ton CO₂ reduced)

Our Own Efforts to Improve Transparency & Understanding

- The IEA Greenhouse Gas Programme (IEA GHG) requires all contractors to use a consistent set of technical and economic premises when evaluating alternative CCS plants and processes
- Carnegie Mellon University (CMU) has developed a computer modeling tool to systematically evaluate plant-level performance and cost of alternative CCS options, based on user-specified inputs
  - Incorporates both current and advanced technologies
  - Integrates CCS with other environmental control systems
  - Characterize key uncertainties in performance and cost
  - Called IECM; Developed for USDOE; publicly available
The IECM is Available At . . .

• Free Web Download:
  - www.iecm-online.com

• Technical Support:
  - PED.modeling@netl.doe.gov

• Other Inquires:
  - mikeb@cmu.edu
  - rubin@cmu.edu

Approach for This Study

• Review and summarize recent (post-2000) CCS cost studies for fossil fuel power plants and other large industrial sources of CO₂
Results of Literature Review

- A wide range of assumptions regarding power plant and capture system design parameters, plant utilization, economic and financial factors
- Most studies report only the cost of capture, excluding costs of CO₂ transport and storage
- Coal plant studies limited largely to bituminous coals (esp. for IGCC)
- Most studies are for new power plants; relatively few on retrofit or repowering of existing plants; relatively few studies of major industrial processes

Results for New Power Plants
(Current Technology)
NGCC Plant with CO₂ Capture

PC Plant with CO₂ Capture
IGCC Plant with CO₂ Capture

Assumptions in CCS Cost Studies

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range in Recent Studies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Size</td>
<td>300 – 800 MW</td>
</tr>
<tr>
<td>Base Plant Efficiency</td>
<td>Subcrit, supercrit, ultraSC, CC</td>
</tr>
<tr>
<td>Fuel Cost &amp; Quality</td>
<td>NG, bitum, subbit, lignite</td>
</tr>
<tr>
<td>Plant Capacity Factor</td>
<td>50% – 95%</td>
</tr>
<tr>
<td>CO₂ Removal Efficiency</td>
<td>85% – 95%</td>
</tr>
<tr>
<td>Capital Charge Rate</td>
<td>11% – 16%</td>
</tr>
</tbody>
</table>

*No single set of assumptions applies everywhere — differences in site-specific factors are the main source of variability in reported CO₂ capture costs*
Reminder

- No one has yet built and operated a CCS system at a large-scale power plant
- Hence, all the costs we’re about to see are projections based on other applications; the “true” costs are not yet known

### Summary of Recent Studies of CO₂ Capture Cost *

(Excludes transport and storage costs; all costs in constant 2002 USD)

<table>
<thead>
<tr>
<th>Cost and Performance Measures</th>
<th>NGCC Plant</th>
<th>PC Plant</th>
<th>IGCC Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. plant emissions (kg CO₂/MWh)</td>
<td>344-379</td>
<td>370</td>
<td>736-811</td>
</tr>
<tr>
<td>Percent CO₂ reduction per MWh (%)</td>
<td>83-88</td>
<td>86</td>
<td>81-88</td>
</tr>
<tr>
<td>Capital cost w/o capture ($/kW)</td>
<td>515-724</td>
<td>570</td>
<td>1161-1486</td>
</tr>
<tr>
<td>Capital cost with capture ($/kW)</td>
<td>909-1261</td>
<td>1000</td>
<td>1894-2578</td>
</tr>
<tr>
<td>Percent increase in capital cost (%)</td>
<td>64-100</td>
<td>76</td>
<td>44-74</td>
</tr>
<tr>
<td>COE w/o capture ($/MWh)</td>
<td>31-50</td>
<td>37</td>
<td>43-52</td>
</tr>
<tr>
<td>COE with capture ($/MWh)</td>
<td>43-72</td>
<td>.54</td>
<td>62-86</td>
</tr>
<tr>
<td>Percent increase in COE w/capture</td>
<td>37-69</td>
<td>46</td>
<td>42-84</td>
</tr>
<tr>
<td>Cost of CO₂ avoided ($/t CO₂)</td>
<td>37-74</td>
<td>53</td>
<td>29-55</td>
</tr>
</tbody>
</table>

* Costs include CO₂ compression; PC and IGCC data are for bituminous coals only; Natural gas prices range from $2.8-4.4/GJ (LHV); Coal prices approx. $1.2/GJ; Other assumptions vary across studies.

Rubin & Davison, CCT 2005
Transport & Storage Costs

- Pipeline transport of CO$_2$ is most widely studied option
- Annualized costs are typically in the range of:
  - $1–5/ton CO$_2$ shipped for on-shore pipelines
  - 40–70% more for off-shore pipelines
- Main focus for CO$_2$ storage is geologic sequestration
- Storage costs are less well characterized and highly variable; most likely range is:
  - $0.5–8.0/ton CO$_2$ stored for deep saline formations
  - Credits of $10–16/ton CO$_2$ for enhanced oil recovery (EOR)

Range of Power Generation Costs Based on Recent Studies*

<table>
<thead>
<tr>
<th></th>
<th>PC</th>
<th>IGCC</th>
<th>NGCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δ(COE)</td>
<td>18–41 (30)</td>
<td>7–27 (17)</td>
<td>13–22 (18)</td>
</tr>
<tr>
<td>Δ(COE)</td>
<td>≈ 18–41 (30)</td>
<td>7–27 (17)</td>
<td>13–22 (18)</td>
</tr>
</tbody>
</table>

*Based on new plants, current technology, bituminous coals and supercritical PC units. Natural gas prices $2.8–4.4/GJ (LHV), coal price ~$1.2/GJ. Other assumptions vary across studies.

Rubin & Davison, CCT 2005
Importance of CCS Energy Penalty

- CCS plants require more fuel input/MWh, typically:
  - PC = +31%; IGCC = +19%; NGCC = +16%
- This loss in efficiency increases the plant-level capital cost ($/kW)_{net} and cost of electricity ($/MWh)_{net}
- CCS energy requirements also increase plant-level fuel use, reagent consumption, and environmental emissions (to air and land) relative to a similar plant without CCS; largest impacts are for PC plants
- However, …net impacts of CCS must be assessed in the context of a particular situation or scenario

Results for Existing Power Plants (Current Technology)
CO₂ Capture at Existing Power Plants

- Retrofitting a CO₂ capture unit is technically feasible but higher in cost than for new plants; site-specific retrofit difficulties may limit applications
- Most cost-effective approaches appear to be:
  - Amine scrubber + supercritical boiler rebuild
  - Repowering with IGCC + CO₂ capture
- Further study is needed to assess & compare options, and their applicability to specific situations

Rubin & Davison, CCT 2005

Advanced Technologies for CO₂ Capture
Examples of New or Improved Technologies Under Development

- Oxyfuel combustion systems
- Advanced (higher efficiency) power generation
  - NGCC, PC and IGCC systems
  - Integrated fuel cell-turbine and other hybrid systems
- Advanced post-combustion and pre-combustion capture technologies
- More efficient industrial processes for production of fuels, chemicals and other products

Implications for Future CCS Costs

- Savings of at least 20–30% are achievable in the near term
- Much more substantial cost reductions expected with continued R&D and the deployment of CCS technologies in the marketplace
- Government policies will play a key role in determining the magnitude and timing of future CCS deployment