Uncertainties in CO$_2$ Capture and Sequestration Costs

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How much does it cost to capture and sequester power plant $CO_2$ emissions?
Factors Affecting Reported Costs of CO$_2$ Capture & Storage (CCS)

- Choice of CCS Technology
- Process Design and Operating Variables
- Economic and Financial Parameters
- Choice of System Boundaries; e.g.,
  - Power plant only vs. partial or complete life cycle
  - One facility vs. multi-plant system (regional, national or global)
  - GHG gases considered (CO$_2$ only vs. all GHGs)
- Time Frame of Interest
  - Current technology vs. future (improved) systems
  - Consideration of technological “learning”
Different Measures of Cost

- **Cost of CO₂ Avoided ($/ton CO₂ avoided)**
  \[
  \text{Cost of CO₂ Avoided} = \frac{(\$/kWh)_{\text{capture}} - (\$/kWh)_{\text{reference}}}{(\text{CO}_2/kWh)_{\text{ref}} - (\text{CO}_2/kWh)_{\text{capture}}}
  \]

- **Cost of CO₂ Abated ($/ton CO₂ reduced)**
  \[
  \text{Cost of CO₂ Abated} = \frac{(\$ \text{ NPV})_{\text{capture}} - (\$ \text{ NPV})_{\text{reference}}}{(\text{CO}_2)_{\text{ref}} - (\text{CO}_2)_{\text{capture}}}
  \]

- **Cost of Electricity ($/MWh)**
  \[
  \text{Cost of Electricity} = \frac{(\text{TCR})(\text{FCF}) + \text{FOM}}{(\text{CF})(8760)(\text{MW})} + \text{VOM} + (\text{HR})(\text{FC})
  \]
Ten Ways to Reduce the Estimated Cost of CO₂ Abatement

10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel costs
7. Assume EOR credits for CO₂ disposal
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!
CMU Project Objectives

• Develop a modeling framework to systematically evaluate the performance and cost of alternative CO$_2$ capture and sequestration options at the level of an individual power plant
• Incorporate both current and advanced technologies for power generation and CO$_2$ capture
• Integrate carbon management technologies with other environmental control systems
• Characterize key uncertainties in performance and cost (of components and the overall system)
Modeling Approach

• Process Technology Models
• Engineering Economic Models
• Systems Analysis Approach
• Advanced Software Capabilities
  ▪ Probabilistic analysis capability
  ▪ User-friendly graphical interface
  ▪ Easy to add or update models
Schematic of CO$_2$ Capture and Storage System

- Coal or Natural Gas
- Air or Oxygen

Energy Conversion Process

CO$_2$ Capture

CO$_2$ Transport

CO$_2$ Storage (Sequestration)

Useful Products (Electricity, Fuels, Chemicals, Hydrogen)
Multi-Pollutant Interactions

Criteria Air Pollutants
- PM
- SO₂
- NOₓ

Hazardous Air Pollutants
- Hg
- HCl
- H₂SO₄

Greenhouse Gas Emissions
- CO₂
- CH₄
IECM-CS Software Package

**Fuel Properties**
- Heating Value
- Composition
- Delivered Cost

**Plant Design**
- Conversion Process
- Emission Controls
- Solid Waste Mgmt
- Chemical Inputs

**Cost Data**
- O&M Costs
- Capital Costs
- Financial Factors

**Power Plant Models**

**Graphical User Interface**

**Plant and Fuel Databases**

**Plant & Process Performance**
- Efficiency
- Resource use

**Environmental Emissions**
- Air, water, land

**Plant & Process Costs**
- Capital
- O&M
- COE
The Model is Publicly Available

• IECM Web Access:
  - www.iecm-online.com

• IECM-CS Beta Test:
  - Contact: abr@cmu.edu

• Technical Support:
  - PED.modeling@netl.doe.gov
An Illustrative Case Study

• Look at cost of current technologies for coal combustion power plants:
  ▪ Amine-based CO₂ capture
  ▪ Pipeline transport
  ▪ Geologic sequestration

• Include *uncertainty* and *variability* in selected performance and cost parameters of the:
  ▪ CO₂ capture system (*30 parameters*)
  ▪ CO₂ transport and storage systems (*3 parameters*)
  ▪ Base power plant (*4 parameters*)
Case Study Plant Configuration

**Combustion Controls**
- **Fuel Type**: Coal
- **NOx Control**: None

**Post-Combustion Controls**
- **NOx Control**: Hot-Side SCR
- **Particulates**: Cold-Side ESP
- **SO2 Control**: Wet FGD
- **Mercury**: None
- **CO2 Capture**: Amine System

**Solids Management**
- **Disposal**: mixed w/ Landfill

**Plant Diagram**
\[ \eta_{\text{CO}_2} = f(L/G, C, y_{\text{in}}, \phi_{\text{lean}}, T_{\text{fg}}, T_{\text{solv}}, H, D) \]
Process Performance Parameters

(italics denotes uncertain or variable parameters)

- Flue gas composition
- Flue gas temp/pressure
- $CO_2$ removal efficiency
- $SO_2$ removal efficiency
- $NO_2$ removal efficiency
- $HCl$ removal efficiency
- MEA concentration
- Lean solvent loading
- Acid gas sorbent loss
- MEA oxidation loss
- Nominal MEA make-up
- Ammonia generation

- Reclaimer chemical reqm’t
- Cooling water makeup
- Flue gas pressure drop
- Fan efficiency
- Solvent pumping head
- Pump efficiency
- Regeneration heat (calc)
- Equiv. elec. requirement
- $CO_2$ product pressure
- $CO_2$ product purity
- Compressor efficiency
- Compression energy
Examples of Parameter Uncertainty Distributions

NORMAL

UNIFORM

LOGNORMAL

TRIANGULAR

BETA

FRACTILE
## Amine System Performance Parameter Uncertainties

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Units</th>
<th>Data (Range)</th>
<th>Nominal Value</th>
<th>Unc. Representation (Distribution Function)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ removal efficiency</td>
<td>%</td>
<td>Mostly 90</td>
<td>90</td>
<td>Uniform (85,95)</td>
</tr>
<tr>
<td>SO₂ removal efficiency</td>
<td>%</td>
<td>Almost 100</td>
<td>99.5</td>
<td>Uniform (99,100)</td>
</tr>
<tr>
<td>NO₂ removal efficiency</td>
<td>%</td>
<td>20-30</td>
<td>25</td>
<td>Uniform (20,30)</td>
</tr>
<tr>
<td>HCl removal efficiency</td>
<td>%</td>
<td>90-95</td>
<td>95</td>
<td>Uniform (90,95)</td>
</tr>
<tr>
<td>Particulate removal eff.</td>
<td>%</td>
<td>50</td>
<td>50</td>
<td>Uniform (40,60)</td>
</tr>
<tr>
<td>MEA concentration</td>
<td>wt%</td>
<td>15-50</td>
<td>30</td>
<td>Uniform (20,30)</td>
</tr>
<tr>
<td>Lean solvent CO₂ loading</td>
<td>mol CO₂/mol MEA</td>
<td>0.15-0.30</td>
<td>0.22</td>
<td>Triangular (0.17,0.22,0.25)</td>
</tr>
<tr>
<td>Nominal MEA make-up</td>
<td>kg MEA/tonne CO₂</td>
<td>0.5-3.1</td>
<td>1.5</td>
<td>Triangular (0.5,1.5,3.1)</td>
</tr>
<tr>
<td>MEA loss (SO₂)</td>
<td>mol MEA/mol SO₂</td>
<td>2</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>MEA loss (NO₂)</td>
<td>mol MEA/mol NO₂</td>
<td>2</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>MEA loss (HCl)</td>
<td>mol MEA/mol HCl</td>
<td>1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>MEA loss (exhaust gas)</td>
<td>ppm</td>
<td>1-4</td>
<td>2</td>
<td>Uniform (1,4)</td>
</tr>
<tr>
<td>NH₃ generation</td>
<td>molNH₃/molMEA ox</td>
<td>1</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Caustic for MEA reclaimer</td>
<td>kg NaOH/tonneCO₂</td>
<td>0.13</td>
<td>0.13</td>
<td>-</td>
</tr>
<tr>
<td>Cooling water makeup</td>
<td>M³/tonne CO₂</td>
<td>0.5-1.8</td>
<td>0.8</td>
<td>Triangular (135,200,480)</td>
</tr>
<tr>
<td>Solvent pumping head</td>
<td>kPa</td>
<td>35-250</td>
<td>207</td>
<td>Triangular (150,207,250)</td>
</tr>
<tr>
<td>Pump efficiency</td>
<td>%</td>
<td>70-75</td>
<td>75</td>
<td>Uniform (70,75)</td>
</tr>
<tr>
<td>Gas-phase pressure drop</td>
<td>kPa</td>
<td>14-30</td>
<td>26</td>
<td>Triangular (14,26,30)</td>
</tr>
<tr>
<td>Fan efficiency</td>
<td>%</td>
<td>70-75</td>
<td>75</td>
<td>Uniform (70,75)</td>
</tr>
<tr>
<td>Equiv. elec. requirement</td>
<td>% regeneration heat</td>
<td>9-19</td>
<td>14</td>
<td>Uniform (9,19)</td>
</tr>
<tr>
<td>CO₂ product purity</td>
<td>wt%</td>
<td>99-99.8</td>
<td>99.5</td>
<td>Uniform (99,99.8)</td>
</tr>
<tr>
<td>CO₂ product pressure</td>
<td>MPa</td>
<td>5.86-15.16</td>
<td>13.79</td>
<td>Triangular (5.86,13.79,15.16)</td>
</tr>
<tr>
<td>Compressor efficiency</td>
<td>%</td>
<td>75-85</td>
<td>80</td>
<td>Uniform (75,85)</td>
</tr>
</tbody>
</table>
**Process Cost Parameters**

*(italics denotes uncertain parameters)*

- Process Area Costs (9)
- Process Facilities Cost
- Eng’g & Home Office
- General Facilities
- Contingency Costs
- Interest d/ Construction
- Royalty Fees
- Pre-production Costs
- Inventory (startup) Cost
- Total Plant Cost
- Total Capital Reqm’t

- Operating Labor
- Maintenance Labor
- Admin./Support Labor
- Maintenance Materials
- Reagent (MEA) Cost
- Chemicals Cost
- Waste Disposal Cost
- Water Cost
- *(Power Cost)*
- $CO_2$ Transport Cost
- $CO_2$ Storage Cost
## CCS Cost Parameter Uncertainties

<table>
<thead>
<tr>
<th>Capital Cost Elements</th>
<th>Nom. Value*</th>
<th>O&amp;M Cost Elements</th>
<th>Nom. Value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Area Costs (9 areas)(^a)</td>
<td>PFC(^b)</td>
<td>Fixed O&amp;M Costs (FOM)</td>
<td></td>
</tr>
<tr>
<td>Total Process Facilities Cost</td>
<td>PFC(^b)</td>
<td>Total Maintenance Cost</td>
<td>2.5 % TPC(^i)</td>
</tr>
<tr>
<td>Engineering and Home Office</td>
<td>7 % PFC(^c)</td>
<td>Maintenance cost</td>
<td>40 % of total maint. cost</td>
</tr>
<tr>
<td>General Facilities</td>
<td>10 % PFC(^d)</td>
<td>allocated to labor</td>
<td></td>
</tr>
<tr>
<td>Project Contingency</td>
<td>15 % PFC(^e)</td>
<td>Admin. &amp; support labor</td>
<td>30 % of total labor</td>
</tr>
<tr>
<td>Process Contingency</td>
<td>5 % PFC(^f)</td>
<td>Operating Labor</td>
<td>2 jobs/shift(^h)</td>
</tr>
<tr>
<td>Total Plant Cost (TPC) = sum of above</td>
<td></td>
<td>Variable O&amp;M Costs (VOM)</td>
<td></td>
</tr>
<tr>
<td>Interest During Construction</td>
<td>calculated</td>
<td>Reagent (MEA) Cost</td>
<td>$1250/tonne MEA(^l)</td>
</tr>
<tr>
<td>Royalty Fees</td>
<td>0.5 % PFC(^g)</td>
<td>Water Cost</td>
<td>$0.2/m(^3)</td>
</tr>
<tr>
<td>Pre-production Costs</td>
<td>1 month(^i)</td>
<td>CO(_2) Transport Cost</td>
<td>$0.02/tonne CO(_2)/km(^m)</td>
</tr>
<tr>
<td>Inventory (startup) Cost</td>
<td>0.5 % TPC(^i)</td>
<td>CO(_2) storage/disposal cost</td>
<td>$5/tonne CO(_2)^n</td>
</tr>
<tr>
<td>Total Capital Reqmt (TCR) = sum of above</td>
<td></td>
<td>Solid waste disposal cost</td>
<td>$175/tonne waste(^b)</td>
</tr>
</tbody>
</table>

*Uncertainty distributions are as follows: \(^a\) The individual process areas modeled are: flue gas blower, absorber, regenerator, solvent processing area, MEA reclaimer, steam extractor, heat exchanger, pumps, CO\(_2\) compressor. The sum of these is the total process facilities cost (PFC). The uncertainty distributions used are: \(^b\)Normal (1.0,0.1), \(^c\)Triangular (5,7,15), \(^d\)Triangular (5,10,15), \(^e\)Triangular (10,15,20), \(^f\)Triangular (2,5,10), \(^g\)Triangular (0,5,0.5), \(^h\)Triangular (0.5,1,1), \(^i\)Triangular (0.4,0.5,0.6), \(^j\)Triangular (1,2,5,5), \(^k\)Triangular (1,2,3), \(^l\)Uniform (1150,1300), \(^m\)Triangular (0.004,0.02,0.06), \(^n\)Chance distribution (-10(p=0.25), -5(p=0.25), 3(p=0.05), 5(p=0.35), 8(p=0.1))
# Case Study Plant Parameters

*(italics denotes uncertain or variable parameters)*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross plant size (MW)</td>
<td>500</td>
<td>Emission standards</td>
<td>2000 NSPS</td>
</tr>
<tr>
<td><em>Gross plant heat rate</em> (kJ/kWh)</td>
<td>9600&lt;sup&gt;a&lt;/sup&gt;</td>
<td>NO&lt;sub&gt;x&lt;/sub&gt; controls</td>
<td>LNB+SCR</td>
</tr>
<tr>
<td><em>Levelized capacity factor</em> (%)</td>
<td>75&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Particulate control</td>
<td>ESP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SO&lt;sub&gt;2&lt;/sub&gt; control</td>
<td>FGD</td>
</tr>
<tr>
<td>Coal Properties</td>
<td></td>
<td>CO&lt;sub&gt;2&lt;/sub&gt; control</td>
<td>MEA</td>
</tr>
<tr>
<td>HHV (kJ/kg)</td>
<td>Low-S: 19346</td>
<td>High-S: 25300</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CO&lt;sub&gt;2&lt;/sub&gt; storage method</td>
<td>Geologic</td>
</tr>
<tr>
<td>% S</td>
<td>0.48</td>
<td>Distance to storage</td>
<td>165 km</td>
</tr>
<tr>
<td>% C</td>
<td>47.9</td>
<td>Cost year (const.$)</td>
<td>2000</td>
</tr>
<tr>
<td><em>Delivered cost</em> ($/tonne)</td>
<td>23.19&lt;sup&gt;c&lt;/sup&gt;</td>
<td>41.37&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Fixed charge factor</td>
<td>0.15&lt;sup&gt;e&lt;/sup&gt;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>Nominal case is a sub-critical unit. Uncertainty case includes supercritical unit. The uncertainty distributions used are:  
<sup>b</sup>Unc = Chance (8968(p=0.5), 9600(p=0.5));  
<sup>c</sup>Unc = Triangular(89,65,75,85);  
<sup>d</sup>Unc = Triangular(15.94,23.19,26.81);  
<sup>e</sup>Unc = Triangular (35.31, 41.97, 51.96)  
<sup>f</sup>Corresponds to a 30-year plant life with a 14.8% real interest rate (or, a 20-year life with 13.9% interest);  
Unc = Uniform(0.10,0.20)
# Cost of Electricity for Reference and CO₂ Capture Plants ($/MWh)

<table>
<thead>
<tr>
<th>Case</th>
<th>Mean</th>
<th>Unc. Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low-S Coal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference Plant w/o CCS</td>
<td>48</td>
<td>34 - 63</td>
</tr>
<tr>
<td>Capture Plant w/ CCS</td>
<td>89</td>
<td>54 – 132</td>
</tr>
<tr>
<td><strong>High-S Coal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference Plant w/o CCS</td>
<td>54</td>
<td>40 - 69</td>
</tr>
<tr>
<td>Capture Plant w/ CCS</td>
<td>96</td>
<td>63 - 138</td>
</tr>
</tbody>
</table>
Case Study Results:
Cost of CO₂ Avoided

Low-S Coal Case

Key variables:
- CO₂ capture efficiency
- steam elect. penalty
- compressor efficiency
- lean sorbent loading
- process facilities cost
- CO₂ storage cost
- variable operating costs
- gross plant heat rate
- plant capacity factor
- fixed charge factor

Uncertainty/Variability in:
- MEA Performance Pars.
- MEA Cost Parameters
- Base Plant Factors (capture plant only)
- no uncertainty

Cumulative Probability

CO₂ Mitigation Cost ($/tonne CO₂ avoided)
Case 2: Current IGCC System

Gasification Options
- Gasifier: Entrained bed
- Oxidant: Oxygen
- Gas Cleanup: Low temp

Post-Combustion Controls
- NOx Control: SCR
- CO2 Control: None

Solids Management
- Slag: Landfill
- Sulfur: Sulfur, Landfill, Sulfuric Acid
Preliminary Results for Current IGCC System w/ CCS

![Cumulative probability vs Mitigation cost graph]

- Deterministic
- Performance uncertainty only
- Cost uncertainties only
- Overall performance + cost uncertainties
Conclusions

- Reported costs of carbon capture and sequestration reflect many assumptions and framings that may not be readily apparent – *User Beware!*
- “Cost” and “price” are often used interchangeably, but mean different things – *User Beware!*
- Based on prevailing assumptions, the estimated cost of CO$_2$ avoided may vary by roughly a factor of three for new coal-based power plants employing current CO$_2$ capture technology and geologic storage.