CO$_2$ Control Options for Fossil Fuel Power Plants in a Multi-Pollutant Framework

Edward S. Rubin and Anand B. Rao
Carnegie Mellon University

5th Electric Utilities Environmental Conference
Tuscon, Arizona
January 22-25, 2002
Options for CO$_2$ Reductions

- Increase plant efficiency
- Switch to low-carbon fuel
- Switch to zero-carbon energy
- Capture & sequester CO$_2$
CO₂ Capture Technologies

CO₂ Separation and Capture

Absorption
- Chemical
  - MEA
  - Caustic
  - Other
- Physical
  - Selexol
  - Rectisol
  - Other

Adsorption
- Adsorber Beds
  - Alumina
  - Zeolite
  - Activated C
- Regeneration Method
  - Pressure Swing
  - Temperature Swing
  - Washing

Cryogenics

Membranes
- Gas Separation
  - Polyphenyleneoxide
  - Polydimethylsiloxane
- Gas Absorption
- Polypropylene
- Ceramic Based Systems

Microbial/Algal Systems
CO$_2$ Sequestration Options

- Geologic Reservoirs
- Enhanced Oil Recovery
- Unmineable Coal Seams
- Oceans
DOE Project Objectives

• Develop a modeling framework to evaluate alternative CO\textsubscript{2} capture and sequestration options at the level of an individual power plant
• Incorporate both current and advanced technologies for capture and power generation
• Integrate carbon management technologies with other environmental control systems
• Characterize key uncertainties in system performance and cost
Modeling Approach

Build on the IECM framework developed for DOE:

- Systems Analysis Approach
- Process Technology Models
- Engineering Economic Models
- Advanced Software Capabilities
  - Probabilistic analysis capability
  - User-friendly graphical interface
  - Easy to add or update models
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
Power Generation Options to be Included in the Model

**Power Generation Technologies**

- **Fuel**
  - Coal
    - Combustion-based
    - Gasification-based
  - Natural Gas
    - Direct Combustion
    - Gas Reforming

- **Oxidant**
  - Air
  - Oxygen

- **Technology**
  - Simple Cycle
    - Pulverized Coal Gas Turbines
  - Combined Cycle
    - Gas Turbines
    - Coal Gasification
    - Fuel Cells
    - Other
CO₂ Capture & Storage Module

- Coal or Natural Gas
- Air or Oxygen

Energy Conversion Processes → CO₂ Capture Options → CO₂ Transport System → CO₂ Storage & Sequestration Options
Multi-Pollutant Interactions

Criteria Air Pollutants
- PM
- SO₂
- NOₓ

Hazardous Air Pollutants
- Hg
- HCl
- H₂SO₄

Greenhouse Gas Emissions
- CO₂
- CH₄
Project Status

• Initial focus on modeling current commercial technologies for combustion-based systems
  ▪ Amine-based CO₂ capture
  ▪ Pipeline transport
  ▪ Geologic sequestration

• Integrated the new CO₂ modules into the IECM-CS framework

• Conducted preliminary case studies of new and retrofit applications
## Case Study of a New PC Plant

<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>Gross plant heat rate (kJ/kWh)</td>
<td>8626</td>
<td>NO\textsubscript{x} controls</td>
<td>LNB +SCR</td>
</tr>
<tr>
<td>Annual avg. capacity factor (%)</td>
<td>75</td>
<td>Particulate control</td>
<td>ESP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SO\textsubscript{2} control</td>
<td>Wet FGD</td>
</tr>
<tr>
<td>Coal characteristics</td>
<td></td>
<td>CO\textsubscript{2} control</td>
<td>MEA</td>
</tr>
<tr>
<td>Rank</td>
<td>Sub-bit.</td>
<td>CO\textsubscript{2} capture efficiency (%)</td>
<td>90</td>
</tr>
<tr>
<td>HHV (MJ/kg)</td>
<td>19.4</td>
<td>CO\textsubscript{2} product pressure (atm)</td>
<td>137</td>
</tr>
<tr>
<td>% S</td>
<td>0.48</td>
<td>Distance to storage site (km)</td>
<td>165</td>
</tr>
<tr>
<td>% C</td>
<td>47.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>% Ash</td>
<td>6.4</td>
<td>Cost year basis (constant dollars)</td>
<td>1999</td>
</tr>
<tr>
<td>Delivered cost ($/ton)</td>
<td>23.19</td>
<td>Fixed charge factor</td>
<td>0.15</td>
</tr>
</tbody>
</table>
## Case Study Plant Configuration

### Combustion Controls
- **Fuel Type**: Coal
- **NOx Control**: In-Furnace Controls

### 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

[Plant Diagram Image]

To Storage
CO₂ Capture Using Amine-Based System

- **Exhaust Gas**
- **Absorber**
- **Blower**
- **Flue Gas**
- **Pump**
- **Cooler**
- **MEA Storage**
- **Flash**
- **Cooler**
- **Regenerator**
- **Reboiler**
- **MEA makeup**
- **H-Ex***
- **Lean-hot**
- **Rich-cool**
- **Rich-hot**
- **CO₂ product**
- **CO₂ Capture Using Amine-Based System**
- **Absorber**
- **Regenerator**
- **Reclaimer**
- **Waste**
Process Performance Parameters

- Flue gas composition
- CO\textsubscript{2} removal efficiency
- SO\textsubscript{2} removal efficiency
- NO\textsubscript{2} removal efficiency
- MEA concentration
- Maximum CO\textsubscript{2} loading
- Lean solvent loading
- Nominal MEA make-up
- Acid gas sorbent loss
- MEA oxidation loss
- Ammonia generation

- Solvent pumping head
- Pump efficiency
- Gas-phase pressure drop
- Fan efficiency
- MEA regeneration heat
- Equiv. elec. requirement
- Reclaimer chemical reqm’t
- CO\textsubscript{2} product pressure
- CO\textsubscript{2} product purity
- Compressor efficiency
- Compression energy
Process Cost 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 Req’m’t
- Operating Labor
- Maintenance Labor
- Admin./Support Labor
- Maintenance Materials
- Reagent (MEA) Cost
- Chemicals Cost
- Waste Disposal Cost
- Water Cost
- Power Cost*
- CO₂ Transport Cost
- CO₂ Storage Cost
Plant Performance Results

Net Plant Capacity
(MW)

Ref. Plant

w/CO₂ Capture

Net Power Gen.
(BkWh/yr)

Ref. Plant

w/CO₂ Capture
Cost of CO$_2$ Avoided

Slope = $53 / \text{ton CO}_2 \text{ avoided}$
Retrofit Costs for Low-S Plant
(Existing plant w/ ESP fully amortized)

Avoided Cost ($/ton CO2)

New FGD Retrofit
- RetroFac=1.25
- Base Case
- + SO2 credit
- + EOR credit

Old FGD Upgrade
- RetroFac=1.25
- Base Case
- + SO2 credit
- + EOR credit
# Amine System Uncertainties

*(Based on current commercial systems)*

<table>
<thead>
<tr>
<th>Performance Parameter</th>
<th>Units</th>
<th>Nominal</th>
<th>Distribution Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ Capture Efficiency</td>
<td>%</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>SO₂ Removal Efficiency</td>
<td>%</td>
<td>99.5</td>
<td>Uniform (99, 100)</td>
</tr>
<tr>
<td>NO₂ Removal Efficiency</td>
<td>%</td>
<td>25</td>
<td>Uniform (20, 30)</td>
</tr>
<tr>
<td>HCl Removal Efficiency</td>
<td>%</td>
<td>95</td>
<td></td>
</tr>
<tr>
<td>MEA Concentration</td>
<td>wt%</td>
<td>30</td>
<td>Triangular (15, 30, 50)</td>
</tr>
<tr>
<td>Max. MEA Loading</td>
<td>mol CO₂/MEA</td>
<td>0.5</td>
<td>Uniform (0.41, 0.63)</td>
</tr>
<tr>
<td>Lean MEA Loading</td>
<td>mol CO₂/MEA</td>
<td>0.15</td>
<td>Triangular (0.10, 0.15, 0.24)</td>
</tr>
<tr>
<td>Nominal MEA Make-up</td>
<td>kg MEA/ton CO₂</td>
<td>1.5</td>
<td>Triangular (0.9, 1.5, 3.1)</td>
</tr>
<tr>
<td>Acid gas-MEA Loss</td>
<td>actual/stoichiometric</td>
<td>1.65</td>
<td></td>
</tr>
<tr>
<td>Ammonia Generation</td>
<td>mol NH₃/MEA oxidized</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Gas Pressure Drop</td>
<td>kPa</td>
<td>5</td>
<td>Triangular (3, 5, 8)</td>
</tr>
<tr>
<td>Solvent Head</td>
<td>kPa</td>
<td>30</td>
<td>Triangular (25, 30, 50)</td>
</tr>
<tr>
<td>Pump Efficiency</td>
<td>%</td>
<td>75</td>
<td>Uniform (70, 75)</td>
</tr>
<tr>
<td>Regeneration Heat</td>
<td>kJ/kg CO₂ recovered</td>
<td>4000</td>
<td>Fractiles ([1800, ..., 5800])</td>
</tr>
<tr>
<td>Heat -&gt; Elec Conversion</td>
<td>%</td>
<td>15</td>
<td>Triangular (10, 15, 20.5)</td>
</tr>
<tr>
<td>Caustic Required</td>
<td>kg soda ash/ton CO₂</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>Activated C Required</td>
<td>kg C/ton CO₂</td>
<td>0.075</td>
<td></td>
</tr>
<tr>
<td>CO₂ Product Pressure</td>
<td>psi</td>
<td>2000</td>
<td>Triangular (1000, 2000, 2200)</td>
</tr>
<tr>
<td>Compressor Efficiency</td>
<td>%</td>
<td>80</td>
<td>Uniform (75, 85)</td>
</tr>
<tr>
<td>Compression Energy Required</td>
<td>kJ/kg CO₂ pdt</td>
<td>f(P2)</td>
<td>Normal (f(P2), 17.8)</td>
</tr>
</tbody>
</table>
Uncertainty in CO$_2$ Mitigation Cost

Uncertainty in:
- MEA Performance
- + Cost Parameters
- + Base Plant Factors
  - (HR, CF, FCF, coal price)

Cumulative Probability

CO$_2$ Mitigation Cost ($/\text{ton CO}_2$ avoided)
Illustrative Benefits of R&D

Cumulative probability

Mitigation cost ($/ton CO₂ avoided)

- At present
- Hypothetical R&D case
Future options will include . . .
IGCC Systems w/ CO$_2$ Capture
NGCC Plants w/ CO₂ Capture

Gasification Options
- **Plant Type**: Combined Cycle

Post-Combustion Controls
- **NOx Control**: SCR
- **CO₂ Control**: None
- **Absorption - MEA**

Solids Management
- **Slag**: Landfill
- **Sulfur**: Landfill

Plant Diagram: CO₂ flowchart with Air and CO₂ streams.
Model Applications

• Process design
• Technology evaluation
• Cost estimation
• R&D management

• Risk analysis
• Environmental compliance
• Marketing studies
• Strategic planning
The Model is Publicly Available

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

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

- **IECM-CS Beta Test:**
  - Contact: rubin@cmu.edu