The Integrated Environmental Control Model (IECM_{cs}):
A Framework and Tool to Evaluate CO\textsubscript{2} Capture and Storage (CCS) Options for Fossil Fuel Power Plants

Edward S. Rubin
Department of Engineering and Public Policy
Carnegie Mellon University
Pittsburgh, Pennsylvania

DOE/NETL Carbon Sequestration Project Review Meeting
Pittsburgh, Pennsylvania
September 27, 2005
Many Factors Affect the Performance and Cost of CCS

- Choice of CO$_2$ capture & storage (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. a 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”
Project Objectives

- Develop a tool to systematically evaluate the plant-level performance and cost of alternative CCS options
- 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)
- Provide user-friendly operation with flexibility and transparency of assumptions

The product: IECM desktop computer model
Modeling Approach

- 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
Schematic of a CCS System

Coal or Natural Gas → Energy Conversion Process → CO₂ Capture → CO₂ Transport → CO₂ Storage (Sequestration)

- Post-combustion
- Pre-combustion
- Oxyfuel combustion
- Pipeline
- Depl. oil/gas fields
- Saline formations
- Coal seams
- Ocean

Air or Oxygen

Useful Products
(Electricity, Fuels, Chemicals, Hydrogen)
Multi-Pollutant Interactions Also are Explicitly Modeled

Criteria Air Pollutants
- PM
- SO\textsubscript{2}
- NO\textsubscript{x}

Greenhouse Gas Emissions
- CO\textsubscript{2}
- CH\textsubscript{4}

Hazardous Air Pollutants
- Hg
- HCl
- H\textsubscript{2}SO\textsubscript{4}

E.S. Rubin, Carnegie Mellon
Model 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

E.S. Rubin, Carnegie Mellon
Partial List of Recent IECM Users

*As of April 2002; approx. 1000 users as of 2005

E.S. Rubin, Carnegie Mellon

ABB
AEP-SCR Engineering
Airborne Technologies
Akzo Nobel Functional Chem
Alberta Economic Development
Alberta Environment
ALCOA Power Generating, Inc.
Allegheny Energy Supply
Alliant Energy
Alstom Power Inc.
American Electric Power
Apogee Scientific, Inc.
Applied Technology Services
Argonne National Laboratory
ATCO Power
Babcock Borsig Power, Inc.
Babcock & Wilcox Co.
Bectel Power Corp.
Black & Veatch Corp.
BOC Gases
Boiler Systems Engineering
Canada Environment
Canada Natural Resources
Carnegie Mellon University
Cinergy Power Generation
Clean Energy Int.
Cogentrix Energy, Inc.
CONSOI Energy, Inc.
Consumers Energy
C&L
CPI
CQ, Inc.

Goodwin Environmental
Great River Energy
Gyeongsang National University
H&W Management Science
Hamon Research Cottrell, Inc.
Harza Engineering
Holland Board of Public Works
IEA Coal Research
Illinois Clean Coal Institute
Illinois Dept. of Natural Resources
Illinois EPA
Illinois Institute of Technology
Indiana Dept. of Env. Mgt.
Intermountain Power Service Corp.
Jack R. McDonald, Inc.
Kansas City Power & Light Co.
KEMA Nederland B.V.
Kinetics
Korea Electric Power Corporation
Korea Institute of Energy Research
Korea Western Power Co.
Krupp Polysius Corp.
LAB SA
Lehigh University
Lower Colorado River Authority
Mail Station PAB338
McDermott Technology, Inc.
MidAmerican Energy Co.
Minnkota Power Cooperative, Inc.
Mitsubishi Heavy Industries, Ltd.
Mitsui Babcock Energy Ltd.
National Park Service
National Power Plc.
NESCAUM
New Hampshire Dept. of Environm.
Nev.
New Jersey DEP
Nicholson Environmental, Inc.
Niksa Energy Associates
NIPSCO
Niro A/S
North Carolina DENR
North Carolina State Univ
Ontario Power Generation
Pacific Corp.
Parsons Technology
Pavilion Technologies, Inc.
Pennsylvania Electric Assoc
PEPCO
PG&E National Energy Group
Pinnacle West Energy
Potomac Electric Power Co.
PowerGen
PPL Generation, LLC
PPL Montana, LLC
Predict Maintenance Tech
Princeton University
Progress Materials, Inc.
PSEG Power LLC
Public Power Institute
Reaction Engineering Intl
Research Triangle Institute
Rhéinbraun Brennstoff GmbH
Sargent & Lundy, LLC
SaskPower
Savvy Engineering, LLC
Scientech
Sierra Pacific Power Co.
Southern Company Services, Inc.
State of New Jersey
Stone & Webster Engineering Corp.
Superior Adsorbents, Inc.
Syncrude
Tampa Electric Co.
Tennessee Valley Authority
Texas Natural Resource Conv Comm
TNO Envi, Energy & Process Innov
TransAlta
TXU Electric
U.S. DOE
U.S. EPA
University of California
University of New Orleans
University of Pittsburgh
URS Corporation
Utah Dept. of Env. Quality
W.L. Gore & Associates, Inc.
Washington Power
Western Kentucky Energy Corp.
Wheelabrator Air PollControl
Wisconsin Dept. of Nat Resources
Wisconsin Electric Power Co.
Wisconsin Energy Corp.
Wisconsin Public Service Corp.
Wisvest-Connecticut, LLC
A Quick Tour of the Model

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

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

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

---

E.S. Rubin, Carnegie Mellon

Integrated Environmental Control Model
Carbon Sequestration Edition

IECM-cs 4.04 (c) 2004, Carnegie Mellon University
Select Plant Type

New Session

Plant Type:
- Combustion (Boiler)
- Combustion (Boiler) [Highlighted]
- Combustion (Turbine)
- IGCC

[Ok] [Cancel]
PC Plant with CO$_2$ Capture

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

To Storage
NGCC Plant with CO$_2$ Capture

Configuration: MEA Scrubber

Post-Combustion Controls

CO$_2$ Capture: Amine System

NGCC CO$_2$ Configuration
IGCC Plant with CO$_2$ Capture

**Gasification Options**
- **Gasifier:** Texaco (Oxygen-blown)
- **Gas Cleanup:** Cold-gas
- **CO2 Control:** Sour Shift + Selexol

**Combustion Controls**
- **NOx Control:** None

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

**Configuration:** Sour Shift + Selexol

**IGCC Base Configuration**
### Set Financial Parameters

#### Table

<table>
<thead>
<tr>
<th>Title</th>
<th>Units</th>
<th>Value</th>
<th>Calc</th>
<th>Min</th>
<th>Max</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year Costs Reported</td>
<td></td>
<td>2000</td>
<td></td>
<td>Menu</td>
<td>Menu</td>
<td>2000</td>
</tr>
<tr>
<td>Constant or Current Dollars?</td>
<td></td>
<td></td>
<td></td>
<td>Menu</td>
<td>Menu</td>
<td>Constant</td>
</tr>
<tr>
<td>Fixed Charge Factor (PFC)</td>
<td>fraction</td>
<td>0.1480</td>
<td>✔️</td>
<td>0.0</td>
<td>1.000</td>
<td>calc</td>
</tr>
<tr>
<td>Discount Rate (Before Taxes)</td>
<td>fraction</td>
<td>0.1030</td>
<td>✔️</td>
<td>0.0</td>
<td>2.000</td>
<td>calc</td>
</tr>
<tr>
<td>Or, specify all the following:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inflation Rate</td>
<td>%/yr</td>
<td>0.0</td>
<td>✔️</td>
<td>0.0</td>
<td>20.00</td>
<td>calc</td>
</tr>
<tr>
<td>Plant or Project Book Life</td>
<td>years</td>
<td>30.00</td>
<td></td>
<td>5.000</td>
<td>60.00</td>
<td>30.00</td>
</tr>
<tr>
<td>Real Bond Interest Rate</td>
<td>%</td>
<td>9.000</td>
<td></td>
<td>0.0</td>
<td>15.00</td>
<td>9.000</td>
</tr>
<tr>
<td>Real Preferred Stock Return</td>
<td>%</td>
<td>8.500</td>
<td></td>
<td>0.0</td>
<td>20.00</td>
<td>8.500</td>
</tr>
<tr>
<td>Real Common Stock Return</td>
<td>%</td>
<td>12.00</td>
<td></td>
<td>0.0</td>
<td>25.00</td>
<td>12.00</td>
</tr>
<tr>
<td>Percent Debt</td>
<td>%</td>
<td>45.00</td>
<td></td>
<td>0.0</td>
<td>100.0</td>
<td>45.00</td>
</tr>
<tr>
<td>Percent Equity (Preferred Stock)</td>
<td>%</td>
<td>10.00</td>
<td></td>
<td>0.0</td>
<td>100.0</td>
<td>10.00</td>
</tr>
<tr>
<td>Percent Equity (Common Stock)</td>
<td>%</td>
<td>45.00</td>
<td>✔️</td>
<td></td>
<td></td>
<td>calc</td>
</tr>
<tr>
<td>Federal Tax Rate</td>
<td>%</td>
<td>35.00</td>
<td></td>
<td>15.00</td>
<td>50.00</td>
<td>35.00</td>
</tr>
<tr>
<td>State Tax Rate</td>
<td>%</td>
<td>4.000</td>
<td></td>
<td>0.0</td>
<td>10.00</td>
<td>4.000</td>
</tr>
<tr>
<td>Property Tax Rate</td>
<td>%</td>
<td>2.000</td>
<td></td>
<td>0.0</td>
<td>5.000</td>
<td>2.000</td>
</tr>
<tr>
<td>Investment Tax Credit</td>
<td>%</td>
<td>0.0</td>
<td></td>
<td>0.0</td>
<td>20.00</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**Process Type:** Overall Plant
### Set Power Block Performance Parameters

<table>
<thead>
<tr>
<th>Title</th>
<th>Units</th>
<th>Unc</th>
<th>Value</th>
<th>Calc</th>
<th>Min</th>
<th>Max</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Turbine/Generator</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Turbine Model</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas Turbine Size (Nominal)</td>
<td>MW</td>
<td></td>
<td>410.5</td>
<td></td>
<td>0.0</td>
<td>5000</td>
<td>GE7FA+</td>
</tr>
<tr>
<td>No. of Gas Turbines</td>
<td>integer</td>
<td></td>
<td>2</td>
<td></td>
<td>Menu</td>
<td>Menu</td>
<td>2</td>
</tr>
<tr>
<td>Inlet Water Content</td>
<td>vol %</td>
<td></td>
<td>33.00</td>
<td></td>
<td>0.0</td>
<td>100.0</td>
<td>calcs</td>
</tr>
<tr>
<td>Turbine Inlet Temperature</td>
<td>deg. F</td>
<td></td>
<td>2420</td>
<td></td>
<td>2000</td>
<td>2500</td>
<td>calcs</td>
</tr>
<tr>
<td>Turbine Back Pressure</td>
<td>psia</td>
<td></td>
<td>2.000</td>
<td></td>
<td>0.0</td>
<td>10.00</td>
<td>calcs</td>
</tr>
<tr>
<td>Adiabatic Turbine Efficiency</td>
<td>%</td>
<td></td>
<td>95.00</td>
<td></td>
<td>0.0</td>
<td>100.0</td>
<td>95.00</td>
</tr>
<tr>
<td>Shaft/Generator Efficiency</td>
<td>%</td>
<td></td>
<td>98.00</td>
<td></td>
<td>0.0</td>
<td>100.0</td>
<td>98.00</td>
</tr>
<tr>
<td>Air Compressor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Ratio (outlet/inlet)</td>
<td>ratio</td>
<td></td>
<td>15.70</td>
<td></td>
<td>1.00</td>
<td>23.00</td>
<td>15.70</td>
</tr>
<tr>
<td>Adiabatic Compressor Efficiency</td>
<td>%</td>
<td></td>
<td>70.00</td>
<td></td>
<td>0.0</td>
<td>100.0</td>
<td>70.00</td>
</tr>
<tr>
<td>Ambient Air Temperature</td>
<td>deg. F</td>
<td></td>
<td>77.00</td>
<td></td>
<td>-50.0</td>
<td>130.0</td>
<td>77.00</td>
</tr>
<tr>
<td>Ambient Air Pressure</td>
<td>psia</td>
<td></td>
<td>14.70</td>
<td></td>
<td>12.00</td>
<td>15.00</td>
<td>14.70</td>
</tr>
<tr>
<td>Combustor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combustor Inlet Pressure</td>
<td>psia</td>
<td></td>
<td>294.0</td>
<td></td>
<td>0.0</td>
<td>330.0</td>
<td>2940</td>
</tr>
<tr>
<td>Combustor Pressure Drop</td>
<td>psia</td>
<td></td>
<td>4.000</td>
<td></td>
<td>0.0</td>
<td>10.00</td>
<td>4.000</td>
</tr>
<tr>
<td>Excess Air For Combustor</td>
<td>% stoich.</td>
<td></td>
<td>177.8</td>
<td></td>
<td>0.0</td>
<td>400.0</td>
<td>calcs</td>
</tr>
</tbody>
</table>

**Process Type:** Power Block
## Get Results for Overall Plant

### Gasification Options
- **Gasifier:** Texaco (Oxygen-blown)
- **Gas Cleanup:** Cold-gas
- **CO2 Control:** Sour Shift + Selexol

### Post-Combustion Controls
- **NOx Control:** None

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

---

**IGCC Case Study**

- **Configure Plant**
- **Set Parameters**
- **Get Results**

- **Overall Plant**
- **Fuel**
- **Air Separation**
- **Gasifier Area**
- **Sulfur Removal**
- **CO2 Capture**
- **Power Block**
- **By-Prod. Mgmt**
- **Stack**

---

**Carnegie Mellon**
Get Results for Plant Mass Balance

<table>
<thead>
<tr>
<th>Plant Inputs</th>
<th>Flow Rate (ton/hr)</th>
<th>Plant Outputs</th>
<th>Flow Rate (ton/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>195.4</td>
<td>Slag</td>
<td>18.48</td>
</tr>
<tr>
<td>Oil</td>
<td>0.6697</td>
<td>Ash Disposed</td>
<td>0.0</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>0.0</td>
<td>Other Solids Disposed</td>
<td>0.0</td>
</tr>
<tr>
<td>Petroleum Coke</td>
<td>0.0</td>
<td>Particulate Emissions to Air</td>
<td>2.591e-03</td>
</tr>
<tr>
<td>Other Fuels</td>
<td>5.860e-02</td>
<td>Captured CO2</td>
<td>464.9</td>
</tr>
<tr>
<td>Total Fuels</td>
<td>196.1</td>
<td>By-Product Ash Sold</td>
<td>0.0</td>
</tr>
<tr>
<td>Lime/Limestone</td>
<td>0.0</td>
<td>By-Product Gypsum Sold</td>
<td>0.0</td>
</tr>
<tr>
<td>Sorbent</td>
<td>0.0</td>
<td>By-Product Sulfur Sold</td>
<td>3.734</td>
</tr>
<tr>
<td>Ammonia</td>
<td>0.0</td>
<td>By-Product Sulfuric Acid Sold</td>
<td>0.0</td>
</tr>
<tr>
<td>Activated Carbon</td>
<td>0.0</td>
<td>Total Solids &amp; Liquids</td>
<td>487.2</td>
</tr>
<tr>
<td>Other Chemicals, Solvents &amp; Catalyst</td>
<td>4.856e-03</td>
<td>See Tab #4 for Total Gases</td>
<td></td>
</tr>
<tr>
<td>Total Chemicals</td>
<td>4.856e-03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process Water</td>
<td>62.25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Process Type: Overall Plant

Carnegie Mellon
Get Results for Specific Components

Carnegie Mellon
Illustrative Case Studies
### Case Study Assumptions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PC</th>
<th>IGCC</th>
<th>NGCC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reference Plant</strong> (~500 MW)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel Type</td>
<td>Pgh #8</td>
<td>Pgh #8</td>
<td>Nat. Gas</td>
</tr>
<tr>
<td>Net HHV Efficiency (%)</td>
<td>39.5</td>
<td>37.5</td>
<td>50.3</td>
</tr>
<tr>
<td>Capacity Factor (%)</td>
<td>75</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Fuel Cost, HHV ($/GJ)</td>
<td>1.2</td>
<td>1.2</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>CCS Plant</strong> (~500 MW&lt;sub&gt;net&lt;/sub&gt;)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt; Capture System</td>
<td>Amine</td>
<td>Shift+Selexol</td>
<td>Amine</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt; Removal (%)</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Pipeline Pressure (MPa)</td>
<td>13.8</td>
<td>13.8</td>
<td>13.8</td>
</tr>
<tr>
<td>Storage Method</td>
<td>Geologic</td>
<td>Geologic</td>
<td>Geologic</td>
</tr>
</tbody>
</table>

*Also: fixed charge factor = 0.148; all costs in constant 2002 US*$

E.S. Rubin, Carnegie Mellon
Cost of CO$_2$ Avoided ($/tonne CO$_2$)
(relative to a similar reference plant without capture)

- **PC**: 51
- **IGCC**: 30
- **NGCC**: 59

**Transport + Storage**
- **PC**: 31
- **IGCC**: 12
- **NGCC**: 41
**Reminder**: Different Assumptions May Give Different Results

**Cost Variations for Amine-Based Coal Plant**

- CO₂ capture efficiency
- steam-electric 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

**Cumulative Probability**

- 1.0
- 0.9
- 0.8
- 0.7
- 0.6
- 0.5
- 0.4
- 0.3
- 0.2
- 0.1
- 0.0

**CO₂ Mitigation Cost ($/tonne CO₂ avoided)**

E.S. Rubin, Carnegie Mellon
Importance of the CCS “Energy Penalty”

• CCS energy requirements are defined here as the *increase in energy input per unit of product output* (relative to a similar plant without capture)

• This measure directly affects the plant-level resource requirements and emissions per MWh of:
  - Fuel and reagent use
  - Air pollutant emissions
  - Solid and liquid wastes
  - Upstream (life cycle) impacts

• Additional energy/MWh for case study plants:
  - PC = 31 %;  IGCC = 16%;  NGCC = 18%
### Summary of CCS Impacts on Resource Use & Emission Rates

<table>
<thead>
<tr>
<th>Capture Plant Parameter&lt;sup&gt;a&lt;/sup&gt;</th>
<th>PC&lt;sup&gt;b&lt;/sup&gt;</th>
<th>IGCC&lt;sup&gt;c&lt;/sup&gt;</th>
<th>NGCC&lt;sup&gt;d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rate</td>
<td>Increase</td>
<td>Rate</td>
</tr>
<tr>
<td><strong>Resource Consumption</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>390</td>
<td>93</td>
<td>361</td>
</tr>
<tr>
<td>Limestone</td>
<td>27.5</td>
<td>6.8</td>
<td>-</td>
</tr>
<tr>
<td>Ammonia</td>
<td>0.80</td>
<td>0.19</td>
<td>-</td>
</tr>
<tr>
<td>CCS Reagents</td>
<td>2.76</td>
<td>2.76</td>
<td>0.005</td>
</tr>
<tr>
<td><strong>Solid Wastes/ Byproduct</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash/slag</td>
<td>28.1</td>
<td>6.7</td>
<td>34.2</td>
</tr>
<tr>
<td>FGD residues</td>
<td>49.6</td>
<td>12.2</td>
<td>-</td>
</tr>
<tr>
<td>Sulfur</td>
<td>-</td>
<td>-</td>
<td>7.53</td>
</tr>
<tr>
<td>Spent CCS sorbent</td>
<td>4.05</td>
<td>4.05</td>
<td>0.005</td>
</tr>
<tr>
<td><strong>Atmospheric Emissions</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>107</td>
<td>−704</td>
<td>97</td>
</tr>
<tr>
<td>SOₓ</td>
<td>0.001</td>
<td>0.29</td>
<td>0.33</td>
</tr>
<tr>
<td>NOₓ</td>
<td>0.77</td>
<td>0.18</td>
<td>0.10</td>
</tr>
<tr>
<td>NH₃</td>
<td>0.23</td>
<td>0.22</td>
<td>-</td>
</tr>
</tbody>
</table>

<sup>a,b,c,d</sup> See Rubin, et.al, Proc. GHGT-7 (2005) for details of case study assumptions
Potential Cost Reductions from Technology Innovation
Potential COE Reductions ($/MWh) for the PC Plant w/Amine Capture

- Plant Derate: 87
- Same Output: 84
- Cheaper Boiler: 81
- Future Amines: 71
- Heat Integr.: 69
- Amine Capex: 68

Reference Plant
Potential Cost Reductions: Cost of CO$_2$ Avoided ($/tonne CO$_2$)
Work in Progress

• **Develop and incorporate models of advanced CO$_2$ capture options and power systems:**
  - Oxyfuel combustion systems
  - ITM oxygen production
  - Advanced IGCC designs

• **Develop more detailed models of CO$_2$ transport and storage:**
  - Regional pipeline transport model
  - Deep saline aquifer storage model
  - EOR storage model
Pipeline Transport Model Structure

**MODEL INPUTS**

- Max. CO₂ Flow Rate
- CO₂ Inlet
- Temperature
- Pipeline Length
- Elevation Change
- CO₂ Inlet Pressure
- CO₂ Outlet Pressure
- Material Roughness
- Number of Pumps
- Pump Pressure Ratio
- Pump Efficiency
- Capacity Factor
- Energy Cost
- Capital Charge Rate

**MODEL OUTPUTS**

- Pipe Diameter
- Total Capital Cost
- Total O&M Cost
- Total Annual Cost
- Total Cost per Tonne

**TRANSPORT MODEL**

- CO₂ Density
- CO₂ Viscosity
- ΔP Per Unit Length
- Reynolds Number
- Friction Factor
- Pump Size
- Pumping Power Required

*E.S. Rubin, Carnegie Mellon*
Aquifer Storage Model Structure

**MODEL INPUTS**
- Max. CO₂ Flow Rate
- CO₂ Surface Injection Pressure
- Reservoir Pressure
- Reservoir Thickness
- Reservoir Depth
- Reservoir Permeability
- Well Diameter

**MODEL OUTPUTS**
- INJECTIVITY MODEL
  - Reservoir Temperature
  - CO₂ Viscosity
  - CO₂ Mobility
  - CO₂ Injectivity
  - Injection Rate per Well
- BHIP CALCULATION
  - Hydrostatic Head
  - Friction Loss
  - Pressure Change

**COST MODEL**
- Site Screening & Evaluation
- Injection Equipment
- Injection Wells
- Production Wells
- Operating Expenses
- Surface Maintenance
- Subsurface Maintenance
- Monitoring & Verification

**Outputs**
- Total Capital Cost
- Total O&M Cost
- Total Annual Cost
- Total Cost per Tonne CO₂
Work in Progress (con’t.)

- **Models of advanced capture options and power systems**
  - Oxyfuel combustion systems
  - ITM oxygen production
  - Advanced IGCC designs

- **More detailed models of CO₂ transport and storage:**
  - Pipeline transport model
  - Saline aquifer storage model
  - EOR storage model

- **Illustrative model applications**
  - Comparative assessments for new or existing plants
  - Assessments of R&D benefits

- **User training and outreach**