The Future Cost of Power Plants with CO$_2$ Capture

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Study Objective

- Develop an empirically-based method to estimate future costs of power plants with CO$_2$ capture, suitable for use in large-scale energy modeling, R&D planning, and other related efforts
Use Powerful Analytical Methods

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Two Approaches to Estimating Future Technology Costs

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

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

*This study employs the latter method*
Study Approach

• Quantify historical learning rates of energy and environmental technologies relevant to power plants with CO₂ capture

• Apply these results to leading plant design options to estimate learning rates and future plant costs

*Note: This study does not include the costs of CO₂ transport and storage technologies*
• Detailed report available from International Energy Agency Greenhouse Gas Programme (IEA GHG)
Retrospective Case Studies
Case Study Technologies

- Flue gas desulfurization systems (FGD)
- Selective catalytic reduction systems (SCR)
- Gas turbine combined cycle system (GTCC)
- Pulverized coal-fired boilers (PC)
- Liquefied natural gas plants (LNG)
- Oxygen production plants (ASU)
- Hydrogen production plants (SMR)
Learning Curve Formulation

General equation:

\[ y_i = ax_i^{-b} \]

where,

- \( y_i \) = time or cost to produce \( i^{th} \) unit
- \( x_i \) = cumulative production thru period \( i \)
- \( b \) = learning rate exponent
- \( a \) = coefficient (constant)

Percent cost reduction for a doubling of cumulative output is called the “learning rate” (LR) = \((1 - 2^{-b})\)
FGD System Capital Costs

(Based on 90% SO₂ removal, 500 MW plant, 3.5%S coal)

Cost reduction = 11% per doubling of installed capacity; 50% reduction over 20 years

y = 1.45x - 0.168
R² = 0.79
SCR System Capital Costs

(Based on 80% NO₂ removal, 500 MW plant, medium S coal)

Cost reduction = 12% per doubling of installed capacity

\[ y = 1.28x^{-0.18} \]

\[ R^2 = 0.75 \]
Early Trend of FGD Capital Cost

Initial cost estimates were a bit optimistic (O&M costs also low)
Early Trend of SCR Cost Estimates

- First Japan commercial installation on a coal-fired power plant
- First German commercial installation
- First US commercial installation
- Early O&M costs also low

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GTCC Capital Costs

Source: Colpier and Cornland (2002).
LNG Plant Capital Costs

\[ y = 269x^{-0.22} \]

\[ R^2 = 0.52 \]
PC Boiler Capital Costs

Subcritical PC Unit Cost (1994)

Cumulative World Pulverized-Coal Plant Installed Capacity (GW)

1942, EF=29.9%

1965

1999, US DOE
EF=37.6%

Pulverized Coal-Fired Boilers

$y = 515.00x^{-0.08}$

PR = 0.95
Oxygen Plant Capital Cost

$y = 94254x^{-0.157}$

$R^2 = 0.43$

Cumulative Oxygen Production since 1980
(Billion cubic feet)
# Case Study Learning Rates

<table>
<thead>
<tr>
<th>Technology</th>
<th>“Best Estimate” Learning Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Capital Cost</td>
</tr>
<tr>
<td>Flue gas desulfurization (FGD)</td>
<td>0.11</td>
</tr>
<tr>
<td>Selective catalytic reduction (SCR)</td>
<td>0.12</td>
</tr>
<tr>
<td>Gas turbine combined cycle (GTCC)</td>
<td>0.10</td>
</tr>
<tr>
<td>Pulverized coal (PC) boilers</td>
<td>0.05</td>
</tr>
<tr>
<td>LNG production</td>
<td>0.14</td>
</tr>
<tr>
<td>Oxygen production (ASU)</td>
<td>0.10</td>
</tr>
<tr>
<td>Hydrogen production (SMR)</td>
<td>0.27</td>
</tr>
</tbody>
</table>

*Results are within ranges reported for other energy-related technologies*
Application to Power Plants
with $CO_2$ Capture
Power Plants with CO$_2$ Capture

- PC plant with post-combustion capture (amine system)
- PC plant with oxyfuel combustion
- NGCC plant with post-combustion capture (amine system)
- IGCC coal plant with pre-combustion capture (WGS + Selexol)
Baseline Plant Designs (1)

PC Plant

Steam Turbine Generator

PC Boiler

Air Pollution Controls (SCR, ESP, FGD)

CO₂ Capture System

CO₂ Compression

CO₂ to storage

Stack

CO₂ to atmosphere

Amine/CO₂ Separation

Mostly N₂

Amine/CO₂


Oxyfuel Plant

Steam Turbine Generator

PC Boiler

Air Separation Unit

Air

O₂

CO₂ to recycle

CO₂ + H₂O

Distillation

CO₂ compression

CO₂ to storage

Stack

CO₂ to atmosphere

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**Step 1**: Disaggregate each plant into major sub-sections

*For example:*

- IGCC Plant Components
  - Air separation unit
  - Gasifier area
  - Sulfur removal/recovery system
  - CO$_2$ capture system (WGS+Selexol)
  - CO$_2$ compression
  - GTCC (power block)
  - Fuel cost
### Step 2: Estimate current plant costs and contribution of each sub-section

**Levelized costs in constant $2002**

<table>
<thead>
<tr>
<th>Plant Type &amp; Technology</th>
<th>Capital Cost</th>
<th>Annual O&amp;M Cost*</th>
<th>Cost of Electricity*</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCC Plant w/ Capture</td>
<td>1,831 $/kW</td>
<td>21.3 $/MWh</td>
<td>62.6 $/MWh</td>
</tr>
<tr>
<td>Air separation unit</td>
<td>18 %</td>
<td>8 %</td>
<td>14 %</td>
</tr>
<tr>
<td>Gasifier area</td>
<td>27 %</td>
<td>17 %</td>
<td>24 %</td>
</tr>
<tr>
<td>Sulfur removal/recovery</td>
<td>6 %</td>
<td>3 %</td>
<td>5 %</td>
</tr>
<tr>
<td>CO₂ capture system*</td>
<td>13 %</td>
<td>7 %</td>
<td>11 %</td>
</tr>
<tr>
<td>CO₂ compression</td>
<td>2%</td>
<td>2 %</td>
<td>2 %</td>
</tr>
<tr>
<td>GTCC (power block)</td>
<td>34 %</td>
<td>9 %</td>
<td>25 %</td>
</tr>
<tr>
<td>Fuel cost**</td>
<td>--</td>
<td>54%</td>
<td>19 %</td>
</tr>
</tbody>
</table>

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*Excludes costs of CO₂ transport and storage  **Based on Pittsburgh #8 coal @ $1.0/GJ
Baseline costs obtained from IECM

- A computer model developed for DOE/NETL, benchmarked on recent engineering studies.

- Provides preliminary design estimates of performance, emissions and cost for:
  - PC, NGCC and IGCC plants
  - Conventional AP controls
  - CCS options (pre- and post-combustion, oxyfuel comb.)

- Free Web Download:
  - www.iecm-online.com
**Step 3**: Select learning rate analogues for each plant component

<table>
<thead>
<tr>
<th>Plant Type &amp; Technology</th>
<th>FGD</th>
<th>SCR</th>
<th>GTCC</th>
<th>PC boiler</th>
<th>LNG prod</th>
<th>O₂ prod</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCC Plant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air separation unit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Gasifier area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Sulfur removal/recovery</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ capture system</td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ compression</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GTCC (power block)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
## Step 4: Estimate current capacity of major plant components

<table>
<thead>
<tr>
<th>Plant Type &amp; Technology</th>
<th>Current $\text{MW}_{\text{net}}$ Equiv.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCC Plant Components</td>
<td></td>
</tr>
<tr>
<td>Air separation units</td>
<td>50,000</td>
</tr>
<tr>
<td>Gasifier area</td>
<td>10,000</td>
</tr>
<tr>
<td>Sulfur removal/recovery</td>
<td>50,000</td>
</tr>
<tr>
<td>$\text{CO}_2$ capture system</td>
<td>10,000</td>
</tr>
<tr>
<td>$\text{CO}_2$ compression</td>
<td>10,000</td>
</tr>
<tr>
<td>GTCC (power block)</td>
<td>240,000</td>
</tr>
</tbody>
</table>

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**Step 5**: Set projection period and start of learning

<table>
<thead>
<tr>
<th>Plant Type</th>
<th>Learning Begins at:</th>
<th>Learning Projected to:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1(^{st}) Plant</td>
<td>n(^{th}) Plant</td>
</tr>
<tr>
<td>NGCC Plant</td>
<td>432</td>
<td>3,000</td>
</tr>
<tr>
<td>PC Plant</td>
<td>500</td>
<td>5,000</td>
</tr>
<tr>
<td>IGCC Plant</td>
<td>490</td>
<td>7,000</td>
</tr>
<tr>
<td>Oxyfuel Plant</td>
<td>500</td>
<td>10,000</td>
</tr>
</tbody>
</table>
Step 6: Sensitivity Analysis

- Learning starts at either first or \( n^{th} \) plant
- Range of component learning rates
- Projection to 50 GW of worldwide capacity
- Lower estimates of current component capacity
- Effect of additional non-CCS experience
- Higher fuel prices for coal and natural gas
- Lower financing costs + higher plant utilization
Detailed results are available in the IEAGHG report.

<table>
<thead>
<tr>
<th>NGCC Sensitivity Case</th>
<th>Capital Cost ($/kW)</th>
<th>COE ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Learning Rate</td>
<td>Initial</td>
</tr>
<tr>
<td>Nominal Base Case Assumptions</td>
<td>0.022</td>
<td>916</td>
</tr>
<tr>
<td>Learning Starts with First Plant</td>
<td>0.014</td>
<td>916</td>
</tr>
<tr>
<td>Learning up to 50 GW</td>
<td>0.018</td>
<td>916</td>
</tr>
<tr>
<td>Current Capture Capacity = 0 GW</td>
<td>0.029</td>
<td>916</td>
</tr>
<tr>
<td>Non-CSS Exp. Multipliers = 2.0</td>
<td>0.030</td>
<td>916</td>
</tr>
<tr>
<td>Natural Gas Price = $6.0/GJ</td>
<td>0.022</td>
<td>925</td>
</tr>
<tr>
<td>FCF = 11%, CF = 85%</td>
<td>0.022</td>
<td>918</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PC Sensitivity Case</th>
<th>Capital Cost ($/kW)</th>
<th>COE ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Learning Rate</td>
<td>Initial</td>
</tr>
<tr>
<td>Nominal Base Case Assumptions</td>
<td>0.021</td>
<td>1,962</td>
</tr>
<tr>
<td>Learning Starts with First Plant</td>
<td>0.013</td>
<td>1,962</td>
</tr>
<tr>
<td>Learning up to 50 GW</td>
<td>0.018</td>
<td>1,962</td>
</tr>
<tr>
<td>Current Capture Capacity = 0 GW</td>
<td>0.026</td>
<td>1,962</td>
</tr>
<tr>
<td>Non-CSS Exp. Multipliers = 2.0</td>
<td>0.029</td>
<td>1,962</td>
</tr>
<tr>
<td>Coal Price = $1.5/GJ</td>
<td>0.021</td>
<td>1,965</td>
</tr>
<tr>
<td>FCF = 11%, CF = 85%</td>
<td>0.021</td>
<td>1,963</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IGCC Sensitivity Case</th>
<th>Capital Cost ($/kW)</th>
<th>COE ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Learning Rate</td>
<td>Initial</td>
</tr>
<tr>
<td>Nominal Base Case Assumptions</td>
<td>0.050</td>
<td>1,831</td>
</tr>
<tr>
<td>Learning Starts with First Plant</td>
<td>0.029</td>
<td>1,831</td>
</tr>
<tr>
<td>Learning up to 50 GW</td>
<td>0.044</td>
<td>1,831</td>
</tr>
<tr>
<td>Current Gasifier Capacity = 1 GW</td>
<td>0.057</td>
<td>1,831</td>
</tr>
<tr>
<td>Above + H2-GTCC = 0 GW</td>
<td>0.088</td>
<td>1,831</td>
</tr>
<tr>
<td>Non-CSS Exp. Multipliers = 2.0</td>
<td>0.062</td>
<td>1,831</td>
</tr>
<tr>
<td>Coal Price = $1.5/GJ</td>
<td>0.050</td>
<td>1,834</td>
</tr>
<tr>
<td>FCF = 11%, CF = 85%</td>
<td>0.048</td>
<td>1,832</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Oxyfuel Sensitivity Case</th>
<th>Capital Cost ($/kW)</th>
<th>COE ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Learning Rate</td>
<td>Initial</td>
</tr>
<tr>
<td>Nominal Base Case Assumptions</td>
<td>0.028</td>
<td>2,417</td>
</tr>
<tr>
<td>Learning Starts with First Plant</td>
<td>0.013</td>
<td>2,417</td>
</tr>
<tr>
<td>Learning up to 50 GW</td>
<td>0.023</td>
<td>2,417</td>
</tr>
<tr>
<td>Current Boiler Capacity = 0</td>
<td>0.054</td>
<td>2,417</td>
</tr>
<tr>
<td>Non-CSS Exp. Multipliers = 2.0</td>
<td>0.038</td>
<td>2,417</td>
</tr>
<tr>
<td>Coal Price = $1.5/GJ</td>
<td>0.028</td>
<td>2,421</td>
</tr>
<tr>
<td>FCF = 11%, CF = 85%</td>
<td>0.028</td>
<td>2,418</td>
</tr>
</tbody>
</table>
Results for IGCC Capital Cost
(Assume learning begins at first capture plant)

Based on nominal case study assumptions

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Summary of Learning Rate Results

(Based on 100 GW of cumulative CCS capacity)
Summary of COE Results
(Based on 100 GW of cumulative CCS capacity)

Percent Reduction in COE

Cost of Electricity ($2002/MWh)

NGCC  PC  IGCC  Oxyfuel

% REDUCTION

FINAL COE
(excluding T&S cost*)

$1/tCO_2 \approx $1/MWh

* $1/tCO_2 = $1/MWh

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## Percentage Reduction in Overall Cost of CO$_2$ Capture

(Based on 100 GW of cumulative CCS capacity)

<table>
<thead>
<tr>
<th>Technology</th>
<th>Capital Cost</th>
<th>Cost of Capture</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGCC, post-comb</td>
<td>20</td>
<td>40</td>
</tr>
<tr>
<td>PC, post-comb</td>
<td>15</td>
<td>26</td>
</tr>
<tr>
<td>IGCC, pre-comb</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Oxyfuel comb</td>
<td>13</td>
<td>13</td>
</tr>
</tbody>
</table>

Capture cost is the difference between plants with and without capture at any point in time. This cost falls more rapidly than the total cost of plants with capture.
Conclusions

• Future reductions in the cost of power plants with CO$_2$ capture will require not only sustained R&D, but also full-scale deployment to foster learning-by-doing

• Results suggest that IGCC plants with CO$_2$ capture have a potential for larger cost reductions compared to combustion-based plants with capture

• The timing and magnitude of future cost reductions are uncertain; policy drivers will play a key role
Caveats

• There are many!

• Please see full report for details.

  ▪ *A spreadsheet model accompanies the report to facilitate analyses with other input assumptions*
Acknowledgements

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- Sonia Yeh

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- Dale Simbeck
- Howard Herzog
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- Leo Schrattenholzer
- Rodney Allam

**Sponsor:**
- IEA GHG (John Davison)
Baseline Plant Designs (2)

NGCC Plant

- Natural Gas
- Combustor
- Gas Turbine
- Steam Turbine Generator
- Steam Generator
- Air Compressor
- Combustor
- Gas Turbine
- Steam Generator
- Air
- Electricity

IGCC Plant

- Coal
- Water
- Gasifier
- Quench System
- Shift Reactor
- Sulfur Removal System
- CO₂ Capture System
- CO₂ Compression
- Gas Turbine Combined Cycle System
- Stack
- Electricity
- to atmosphere

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