The Future of Coal-Based Power Generation With CCS

UN CCS Summit
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MIT Energy Initiative
web.mit.edu/coal/

MIT: The Future of Coal
Times Are Changing

As Yogi Berra said:

“The Future Ain’t What It Used to Be”
Overview

- **Coal-Based Electricity Generating Technologies**
  - Without and with CO₂ capture
  - Criteria emissions performance today and future potential
  - Cost and performance impacts

- **CO₂ Transport and Sequestration**

- **Conclusions**

- **A Forward View**

Coal is and will remain, by necessity, a key component in our electricity generating portfolio for the foreseeable future.
Base Design Conditions for Generation Technologies

• New greenfield unit
• Emissions controlled to below today’s best demonstrated performance
• Illinois # 6 high-sulfur bituminous coal
• Used Carnegie-Mellon model for consistent design comparisons
• Costs based on 2000 to 2004 detailed design costs; indexed to 2007 $ with process construction cost index
• Integrated existing commercial technology
• Single-condition indicative cost comparisons done; coal type, site, location, etc. will affect cost numbers
• Important issue is comparison among technologies w/o and w CO₂ capture
Advanced PC Power Plant
The New Generation of Power Plants

Neideraussem Lignite-fired Power Plant, 965 MWe (net), 43.3% (HHV)

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PC Power Plant Schematic

Combustion Block

Flue Gas
T = 149 C
O₂ = 5%
CO₂ = 11%

Steam Cycle Block

Steam Gas Treatment

Stack Gas
T = 55 C

500 MW

Air
Coal

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PC Thermal Efficiencies

• **Sub-Critical Unit**
  - Operation to 1025 °F and 3200 psi
  - 33 to 37 % (HHV)

• **Supercritical Unit**
  - Typical operation 1050 °F and 3530 psi
  - 37 to 42 % (HHV)

• **Ultra-Supercritical Unit**
  - Typical 1110-1140 °F and 4650 psi
  - 42 to 45 % (HHV)
PC Plant with Amine-Based CO₂ Capture

- Generating efficiency is 29.3% for new supercritical plant with CO₂-capture; down from 38.5% for supercritical no-capture plant; a 9.2 percentage point drop.
- To maintain constant electrical output requires 32% increase in coal consumption.

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Oxygen-Driven Power Generation

Issue: Low flue-gas CO$_2$ concentration due to high nitrogen dilution causes large impact of capture

- **Solution:** Substitute oxygen for air eliminating the nitrogen dilution, compress flue gas directly [Oxy-fuel PC combustion]

- **Solution:** Gasify the coal and remove the CO$_2$ at high pressure [IGCC]
Oxy-Fuel PC Generation/Capture

- Of interest only for CO₂ capture for sequestration
- Addresses the issue of high energy costs for capture and recovery
- Requires air separation unit and associated energy usage

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Oxy-Fuel PC Generation/Capture

• Current Status
  – Active pilot-scale development
  – Vattenfall planned new 30 MW$_{th}$ CO$_2$-free coal steam plant with 2008 start-up in Germany
  – Hamilton, Ohio planning 25 MW$_e$ 1963 power boiler retrofit, 2009 start-up

• Oxy-Fuel PC shows potential of lower COE and lower CO$_2$ avoided cost than other PC capture technologies
IGCC Plant

- Gasifier type is biggest variable:
- Texaco & E Gas: slurry feed & higher pressure, ~39% efficiency potential
- Shell: dry feed and lower pressure, more costly, ~41% efficiency potential
The Shift reaction converts CO to CO₂ & hydrogen; the CO₂ is then removed.

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## Performance and Costs of Generating Technologies

<table>
<thead>
<tr>
<th></th>
<th>Subcritical PC</th>
<th>Supercritical PC</th>
<th>Oxy-Fuel PC</th>
<th>IGCC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>w/o capture</td>
<td>w/ capture</td>
<td>w/o capture</td>
<td>w/ capture</td>
</tr>
<tr>
<td>PERFORMANCE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Rate, Btu/kWe-h</td>
<td>9,950</td>
<td>13,600</td>
<td>8,870</td>
<td>11,700</td>
</tr>
<tr>
<td>Efficiency (HHV)</td>
<td>34.3%</td>
<td>25.1%</td>
<td>38.5%</td>
<td>29.3%</td>
</tr>
<tr>
<td>CO₂ emitted, g/kWe-h</td>
<td>931</td>
<td>127</td>
<td>830</td>
<td>109</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COSTS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Plant Cost, $/kWe</td>
<td>$1,580</td>
<td>$2,760</td>
<td>$1,650</td>
<td>$2,650</td>
</tr>
<tr>
<td>Inv. Charge, ¢/kWe-h @ 15.1%</td>
<td>3.20</td>
<td>5.60</td>
<td>3.35</td>
<td>5.37</td>
</tr>
<tr>
<td>Fuel, ¢/kWe-h @ $1.50/MMBtu</td>
<td>1.49</td>
<td>2.04</td>
<td>1.33</td>
<td>1.75</td>
</tr>
<tr>
<td>O&amp;M, ¢/kWe-h</td>
<td>0.75</td>
<td>1.60</td>
<td>0.75</td>
<td>1.60</td>
</tr>
<tr>
<td>COE, ¢/kWe-h</td>
<td>5.45</td>
<td>9.24</td>
<td>5.43</td>
<td>8.72</td>
</tr>
<tr>
<td>Cost of CO₂ avoided vs. same technology w/o capture, $/tonne</td>
<td>47.1</td>
<td>45.7</td>
<td>34.0</td>
<td>22.3</td>
</tr>
</tbody>
</table>


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### Emissions Performance

<table>
<thead>
<tr>
<th>Technology</th>
<th>Case</th>
<th>Particulates</th>
<th>SO₂</th>
<th>NOₓ</th>
<th>Mercury</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>lb/MM Btu</td>
<td>lb/MM Btu</td>
<td>lb/MM Btu</td>
<td>% removed</td>
</tr>
<tr>
<td><strong>PC Plant</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Typical</td>
<td></td>
<td>0.02</td>
<td>0.22</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Best Commercial</td>
<td></td>
<td>0.015 (99.5%)</td>
<td>0.04 (99+%%)</td>
<td>0.03 (90+%%)</td>
<td>90</td>
</tr>
<tr>
<td>Design w CO₂ Cap.</td>
<td></td>
<td>0.01 (99.5+%%)</td>
<td>0.0006 (99.99%)</td>
<td>0.03 (95+%%)</td>
<td>75-85</td>
</tr>
<tr>
<td><strong>IGCC Plant</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Best Commercial</td>
<td></td>
<td>0.001</td>
<td>0.015 (99.8%)</td>
<td>0.01</td>
<td>95</td>
</tr>
<tr>
<td>Design w CO₂ Cap.</td>
<td></td>
<td>0.001</td>
<td>0.005 (99.9%)</td>
<td>0.01</td>
<td>&gt;95</td>
</tr>
</tbody>
</table>

PC emissions control technology continues to improve; further, emissions reductions potential exists. Design case with CO₂ capture from recent EPRI evaluation.

IGCC emissions performance (best commercial) is well below current requirements and can be further improved; should be similar to NGCC.
### Incremental Costs of Advanced PC Emissions Control Vs. No-Control

<table>
<thead>
<tr>
<th></th>
<th>Capital Cost* [$/kWₑ]</th>
<th>O&amp;M [¢/kWₑ-h]</th>
<th>COE** [¢/kWₑ-h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM control</td>
<td>50</td>
<td>0.18</td>
<td>0.28</td>
</tr>
<tr>
<td>NOₓ</td>
<td>32</td>
<td>0.11</td>
<td>0.17</td>
</tr>
<tr>
<td>SO₂</td>
<td>190</td>
<td>0.22</td>
<td>0.60</td>
</tr>
<tr>
<td>Incremental control cost</td>
<td>273</td>
<td>0.51</td>
<td>1.05***</td>
</tr>
</tbody>
</table>

* Incremental capital costs are for a new-build plant
** Incremental COE impact for Illinois #6 coal with 99.3 % PM reduction, 99.4% SOx reduction, and >90 % NOx reduction.
*** When this is added to the “no-control” COE for SC PC, the total COE is 5.5 ¢/kWₑ-h.

Note: To reduce emissions by a factor of two further would increase the cost by about an additional 0.25 ¢/kWₑ-h.

**Today’s high levels of emissions control increase the cost of electricity by ~1 ¢/kWₑ-h out of about 5.5 ¢/kWₑ-h or about 20 %.

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Carbon Capture and Sequestration (CCS)

- Coal or Natural Gas
- Air or Oxygen

Energy Conversion Process

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

Useful Products
(Electricity, Fuels, Chemicals, Hydrogen)
Location of Saline Aquifers, Oil and Gas Fields, and Coal Plants

By Capacity (MW)
- * 0 - 250
- 251 - 1000
- 1001 - 4000

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Total Coal-Fired Capacity = 330 GW
A Potential CCS Power Plant Project

Planning for a CCS-enabled power plant must include a robust CO₂ storage plan for all phases of the plant’s operations over its entire half-century operational lifetime.

CO₂ pipeline and injector wells used during the subsequent decades of full plant operations.

Initial CO₂ pipeline and injector well used during plant start up and validation phase.

CO₂ pipeline and injector wells used during the first decade of full plant operations.
## CO₂ Capture Through Sequestration*

<table>
<thead>
<tr>
<th>Technology</th>
<th>PC</th>
<th>IGCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCS Step</td>
<td>$/kW_{e-h}$</td>
<td>$/kW_{e-h}$</td>
</tr>
<tr>
<td>Capture</td>
<td>2.7</td>
<td>1.21</td>
</tr>
<tr>
<td>Compression</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Transport</td>
<td>0.19</td>
<td>0.18</td>
</tr>
<tr>
<td>Injection</td>
<td>0.68</td>
<td>0.64</td>
</tr>
<tr>
<td>Totals</td>
<td>4</td>
<td>2.4</td>
</tr>
</tbody>
</table>

- There are no apparent technical or economic show-stoppers to CCS today.
- Bus Bar COE increase in about 50%.

* Costs are estimates for existing CCS technology with Illinois #6 Coal; they will vary with coal type, with generating technology, with site and with reservoir properties. Here, they are meant to be indicative of relative magnitude.
The Future of Coal

- Although the COE for IGCC is lower for Bituminous coal, differences narrow for lower rank coals and at elevation; cost improvements for PC could further narrow the gap. Also, Oxy-fuel PC looks competitive.

- It is too early to pick winners for coal-based power generation with capture.

- Emissions from coal-based power generation can be very low; and with CO$_2$ capture, even lower, to the extent of really being very clean.

- With CO$_2$ capture and sequestration, coal can provide electricity at a cost competitive with wind and nuclear.

- Thus, coal would appear to continue to be an economic choice for baseload generation of very low emissions electricity, including low CO$_2$ emissions.
CCS – Findings and Observations

• Technologies for CO$_2$ capture with generation are all commercial, but will benefit from operation at scale to improve cost/performance

• Current information indicates that it is technically feasible to safely store large quantities of CO$_2$ in saline aquifers, and the storage capacity of such aquifers is very large. However, there are issues that require resolution

• Broad range of regulatory issues require resolution (permitting, liability, monitoring, ownership,…)

• Need to gain political and public confidence in the safety and efficacy of geologic sequestration
MIT Coal Report Recommendations

• Solid technical program to resolve scientific & technical issues associated with injection & storage of Gt quantities of CO$_2$/yr

• In the U.S., 3 to 5 large-scale CCS demonstration projects of 1 million tonnes CO$_2$ per year, using different generation technologies, focusing on different geologies, and operated for several years to resolve outstanding technical, scientific, liability, policy, and regulatory issues

• Effectively demonstrate dynamic operation of fully-integrated infrastructure systems including coal conversion, CO$_2$ capture, CO$_2$ transport, and CO$_2$ injection in a continuously operating manner over extended time periods.

This research and demonstration program is needed to develop the required information in a timely manner so that we have robust technology options available to apply when society decides to manage CO$_2$ emissions from power generation and other major stationary sources.
Thank you