The Outlook for Improved CO₂ Capture Systems

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Special Energy Science Colloquium
Swiss Federal Institute of Technology (ETH)
Zurich, Switzerland
March 4, 2009

Outline of Talk

• What is the current status of CO₂ capture technology?
• What is the outlook for improved technology?
• What is needed to realize these improvements?
Many Ways to Capture CO₂

CO₂ Separation and Capture

Absorption
- Chemical
  - MEA
  - Amine
- Physical
  - Solvent
  - Rectisol
  - Other

Adsorption
- Adsorber Beds
- Alumina
- Zeolite
- Activated C

Cryogenics
- Pressure Swing
- Temperature Swing
- Washing

Membranes
- Regeneration Method
- Gas Separation
- Polyphenyleneoxide
- Polydimethylsiloxane

Microbial/Algal Systems
- Gas Absorption
- Polysulfone
- Ceramic based Systems

Choice of technology depends strongly on application

Schematic of Carbon Capture and Storage (CCS)

Energy Conversion Process
- Carbonaceous Fuels
- Air or Oxygen
- CO₂ Capture & Compress
- Useful Products (Electricity, Fuels, Chemicals, Hydrogen)
- CO₂ Transport
- Pipeline
- Tanker
- Post-combustion
- Pre-combustion
- Oxyfuel combustion

CO₂ Storage (Sequestration)
- CO₂ Storage (Sequestration)
- Depleted oil/gas fields
- Deep saline formations
- Unmineable coal seams
- Ocean
- Mineralization
**CO₂ Capture Options for Power Plants**

Source: IPCC SRCCS, 2005

- **Post combustion**
  - Coal
  - Biomass
  - Air
  - Power & Heat
  - CO₂ Capture

- **Pre combustion**
  - Gasification
  - Gas, Oil
  - Power & Heat
  - CO₂ Separation

- **Oxyfuel**
  - Coal Gas
  - Biomass
  - Air
  - Power & Heat
  - CO₂ Compression & Dehydration

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**Status of Capture Technology**

- CO₂ capture technologies are commercial and widely used in industrial processes, mainly in the petroleum and petrochemical industries (e.g., for ammonia production and processing of natural gas)

- CO₂ capture also has been applied to several gas-fired and coal-fired boilers (to produce commodity CO₂ for sale), but at scales that are small compared to a large modern power plant

- Integration of CO₂ capture, transport and geologic sequestration has been demonstrated in several industrial applications, but not yet at an electric power plant

Source: E.S. Rubin, Carnegie Mellon
Current CO₂ Capture Projects

Examples of Post-Combustion CO₂ Capture at Coal-Fired Plants

Shady Point Power Plant
(Panama, Oklahoma, USA)

Warrior Run Power Plant
(Cumberland, Maryland, USA)
Examples of Post-Combustion CO$_2$ Capture at Gas-Fired Plants

- Bellingham Cogeneration Plant (Bellingham, Massachusetts, USA)
- Petronas Urea Plant Flue Gas (Keda, Malaysia)

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Examples of Pre-Combustion CO$_2$ Capture Systems

- Petcoke Gasification to Produce H$_2$ (Coffeyville, Kansas, USA)
- Coal Gasification to Produce SNG (Beulah, North Dakota, USA)

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Example of Oxyfuel Combustion Capture System

Vattenfall Schwarze Pumpe Station
(Germany)

CO₂ Pipelines for Enhanced Oil Recovery

Source: USDOE/Battelle

Source: NRDC

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Geological Storage of Captured CO$_2$ with Enhanced Oil Recovery (EOR)

Weyburn Field, Canada

Dakota Coal Gasification Plant, ND

Sources: IEAGHG; NRDC; USDOE

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Geological Storage of Captured CO$_2$ in a Deep Saline Formation

Sleipner Project (Norway)

Source: Statoil

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Geological Storage of Captured CO₂ in a Deep Saline Formation

In Salah / Krechba (Algeria)

Illustrative CO₂ Emission Rates for New Power Plants (kg CO₂/MWh)

Typical emission reduction is 85-86% based on CO₂ avoided (for ~90% capture)
Cost of New Power Plants with and without CCS

Typical Cost of CO₂ Avoided
(Relative to a SCPC reference plant w/o CCS)

Levelized cost in 2007 US$ per tonne CO₂ avoided (based on current technology w/ bituminous coals)

<table>
<thead>
<tr>
<th>Power Plant System (relative to SCPC plant without CCS)</th>
<th>New Supercritical Pulverized Coal Plant</th>
<th>New Integrated Gasification Combined Cycle Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep aquifer storage</td>
<td>~ $70 /tCO₂</td>
<td>~ $50 /tCO₂</td>
</tr>
<tr>
<td>Enhanced oil recovery (EOR) storage</td>
<td>Cost reduced by ~ $20–30 /tCO₂</td>
<td></td>
</tr>
</tbody>
</table>

Source: Based on IPCC, 2005; Rubin et al., 2007; DOE, 2007

Different choices of reference plant without CCS will yield different avoidance costs
Importance of the CCS “Energy Penalty”

- CCS energy requirements = *increase in fuel energy input per unit of net electrical output* (relative to a similar plant without capture)

- Representative values for new power plants:
  - PC = 31%;  IGCC = 16%;  NGCC = 17%

- This has a major impact on plant-level capital cost ($/kW), generation cost ($/MWh), resource requirements and emissions per MWh

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What is the outlook for improved capture technology?
Major R&D Efforts Worldwide

- Australia
- Canada
- European Union
- Japan
- United States

All have significant ongoing programs in carbon capture and sequestration

What About Future Costs?

Future CCS Costs

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Two Approaches to Estimating Future Technology Costs

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

The IECM Project: Power Plant Performance, Emissions & Costs

- A desktop/laptop computer model developed for DOE/NETL; free and publicly available at: [www.iecm-online.com](http://www.iecm-online.com)
- Provides systematic estimates of performance, emissions, costs and uncertainties for preliminary design of:
  - PC, IGCC and NGCC plants
  - All flue/fuel gas treatment systems
  - CO₂ capture and storage options (pre- and post-combustion, oxy-combustion; transport, storage)
**Recent IECM Applications:**
Potential Cost Reductions from R&D

**USDOE Outlook for PC Plants**

**Cost of CO₂ Avoided ($/tonne CO₂)**

- **Plant Derate**
- **Same Output**
- **Cheaper Boiler**
- **Future Amines**
- **Heat Integr.**
- **Amine Capex**

**28% reduction in COE**

**Source:** NETL, 2006

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**USDOE Outlook for IGCC Plants**

19% reduction in COE

Source: NETL, 2006

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**USDOE Outlook for Oxyfuel Plants**

19% reduction in COE

Source: NETL, 2006

E. S. Rubin, Carnegie Mellon
Two Approaches to Estimating Future Technology Costs

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

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

Historical Cost Trends for Emerging Energy Technologies

Cost reductions tend to come with increased deployment and use of a new technology

Source: IIASA, 1996
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) = \((1 - 2^{-b})\)

Application to CO\(_2\) Capture

- Quantify historical learning rates of energy and environmental technologies relevant to power plants with CO\(_2\) capture
- Apply these results to leading plant design options to estimate learning rates and future costs of power plants with CO\(_2\) capture*

* Excludes the costs of CO\(_2\) transport and storage
Retrospective Case Studies

- 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)

FGD System Capital Costs

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

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

R² = 0.79

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SCR System Capital Costs

Cost reduction = 12% per doubling of installed capacity

Early Trend of FGD Capital Cost

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

![Graph showing early trend of SCR cost estimates with key events marked: First Japan commercial installation on a coal-fired power plant in 1983, First German commercial installation in 1989, and First US commercial installation in 1993. The graph also indicates that early O&M costs were low.]

GTCC Capital Costs

![Graph showing GTCC capital costs with investment price USD (1990$/kW) on the vertical axis and cumulative installed capacity, MW, on the horizontal axis. The graph indicates a decrease in investment costs with increasing cumulative installed capacity.][5]

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

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

\[ R^2 = 0.52 \]

PC Boiler Capital Costs

\[ y = 515.00x^{-0.08} \]

\[ PR = 0.95 \]

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**Oxygen Plant Capital Cost**

- Equation: \( y = 94254x^{-0.157} \)
- \( R^2 = 0.43 \)

**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*
Baseline CCS Plant Designs (1)

PC Plant

- Steam Turbine Generator
- PC Boiler
- Air Pollution Controls (SCR, ESP, FGD)
- CO₂ Capture System
- Air Separation Unit
- Steam
- CO₂ Compression
- CO₂ to storage
- to atmosphere

Oxyfuel Plant

- Steam Turbine Generator
- PC Boiler
- Air Pollution Controls (SCR, ESP, FGD)
- CO₂ Capture System
- Air Separation Unit
- Steam
- CO₂ Compression
- CO₂ to storage
- to atmosphere

Baseline CCS Plant Designs (2)

NGCC Plant

- Compressor
- Gas Turbine
- Steam Turbine Generator
- Steam
- CO₂ Capture System
- Nearly N₂
- Sulfur Removal System
- CO₂ Capture System
- Gas Turbine Combined Cycle System
- CO₂ to storage
- to atmosphere

IGCC Plant

- Gasifier
- Air Separation Unit
- Quench System
- Shift Reactor
- Sulfur Removal System
- CO₂ Capture System
- Selexol/CO₂ Separation
- CO₂ to storage
- to atmosphere
Baseline Plant Characteristics

- Approximately 500 MW net output
- Supercritical PC and Quench gasifier IGCC
- Pittsburgh #8 bituminous coal
- 75% levelized capacity factor
- 14.8% fixed charge factor
- All costs in constant 2002 dollars

Step 1: Disaggregate each plant into major sub-sections

For example:

- IGCC Plant Components
  - Air separation unit
  - Gasifier area
  - Sulfur removal/recovery system
  - CO₂ capture system (WGS+Selexol)
  - CO₂ 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 $/MWh</td>
</tr>
<tr>
<td>Air separation unit</td>
<td>18 %</td>
<td>8 %</td>
<td>14 %</td>
</tr>
<tr>
<td>Gasifier area</td>
<td>27 %</td>
<td>17 %</td>
<td>24 %</td>
</tr>
<tr>
<td>Sulfur removal/recovery</td>
<td>6 %</td>
<td>3 %</td>
<td>5 %</td>
</tr>
<tr>
<td>CO$_2$ capture system*</td>
<td>13 %</td>
<td>7 %</td>
<td>11 %</td>
</tr>
<tr>
<td>CO$_2$ 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>

*Excludes costs of CO$_2$ transport and storage  **Based on Pittsburgh #8 coal @ $1/GJ

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**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>O$_2$ 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>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO$_2$ capture system</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO$_2$ 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>

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### Step 4: Estimate current capacity of major plant components

<table>
<thead>
<tr>
<th>Plant Type &amp; Technology</th>
<th>Current MW&lt;sub&gt;net&lt;/sub&gt;</th>
<th>Equiv.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGCC Plant Components</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air separation units</td>
<td>50,000</td>
<td></td>
</tr>
<tr>
<td>Gasifier area</td>
<td>10,000</td>
<td></td>
</tr>
<tr>
<td>Sulfur removal/recovery</td>
<td>50,000</td>
<td></td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt; capture system</td>
<td>10,000</td>
<td></td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt; compression</td>
<td>10,000</td>
<td></td>
</tr>
<tr>
<td>GTCC (power block)</td>
<td>240,000</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Plant Type</th>
<th>Cumulative CCS Capacity (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Learning Begins at:</td>
</tr>
<tr>
<td></td>
<td>1&lt;sup&gt;st&lt;/sup&gt; Plant</td>
</tr>
<tr>
<td>NGCC Plant</td>
<td>432</td>
</tr>
<tr>
<td>PC Plant</td>
<td>500</td>
</tr>
<tr>
<td>IGCC Plant</td>
<td>490</td>
</tr>
<tr>
<td>Oxyfuel Plant</td>
<td>500</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

Results for IGCC Capital Cost
(Assuming learning begins at first capture plant)

Based on nominal case study assumptions
### Detailed results available in papers and reports

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

<table>
<thead>
<tr>
<th>Case</th>
<th>Capital Cost ($/kW)</th>
<th>COE ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NGCC Sensitivity Case</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal Base Case Assumptions</td>
<td>0.011 1.962 1.793 9.1%</td>
<td>0.017 72.9 62.8 14.1%</td>
</tr>
<tr>
<td>Learning Starts with First Plant</td>
<td>0.015 1.962 1.746 13.1%</td>
<td>0.024 73.4 63.8 14.4%</td>
</tr>
<tr>
<td>Current Capture Capacity = 0 GW</td>
<td>0.013 1.962 1.733 12.7%</td>
<td>0.023 73.4 62.5 14.5%</td>
</tr>
<tr>
<td>Non-CSS Exp. Multipliers = 2.0</td>
<td>0.012 1.962 1.712 12.5%</td>
<td>0.022 73.4 60.8 14.7%</td>
</tr>
<tr>
<td>Coal Price = $1.5/GJ</td>
<td>0.011 1.962 1.699 12.4%</td>
<td>0.021 73.4 59.3 14.8%</td>
</tr>
<tr>
<td>FCF = 11%, CF = 85%</td>
<td>0.010 1.962 1.689 12.3%</td>
<td>0.020 73.4 57.8 14.9%</td>
</tr>
<tr>
<td><strong>PC Sensitivity Case</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal Base Case Assumptions</td>
<td>0.009 1.831 1.705 9.6%</td>
<td>0.015 62.6 54.9 17.1%</td>
</tr>
<tr>
<td>Learning Starts with First Plant</td>
<td>0.013 1.831 1.649 13.6%</td>
<td>0.022 62.6 55.9 17.2%</td>
</tr>
<tr>
<td>Current Capture Capacity = 0 GW</td>
<td>0.012 1.831 1.643 13.2%</td>
<td>0.021 62.6 54.6 17.3%</td>
</tr>
<tr>
<td>Non-CSS Exp. Multipliers = 2.0</td>
<td>0.011 1.831 1.624 12.8%</td>
<td>0.020 62.6 53.4 17.4%</td>
</tr>
<tr>
<td>Coal Price = $1.5/GJ</td>
<td>0.010 1.831 1.607 12.4%</td>
<td>0.019 62.6 52.1 17.5%</td>
</tr>
<tr>
<td>FCF = 11%, CF = 85%</td>
<td>0.009 1.831 1.591 12.3%</td>
<td>0.018 62.6 50.8 17.6%</td>
</tr>
<tr>
<td><strong>IGCC Sensitivity Case</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal Base Case Assumptions</td>
<td>0.008 1.702 1.567 10.5%</td>
<td>0.015 52.5 45.1 17.3%</td>
</tr>
<tr>
<td>Learning Starts with First Plant</td>
<td>0.012 1.702 1.506 14.3%</td>
<td>0.021 52.5 46.9 17.5%</td>
</tr>
<tr>
<td>Current Capture Capacity = 1 GW</td>
<td>0.011 1.702 1.496 14.1%</td>
<td>0.020 52.5 45.8 17.6%</td>
</tr>
<tr>
<td>Above + IG-GTCC = 0 GW</td>
<td>0.010 1.702 1.478 13.9%</td>
<td>0.019 52.5 44.6 17.7%</td>
</tr>
<tr>
<td>Non-CSS Exp. Multipliers = 2.0</td>
<td>0.009 1.702 1.460 13.7%</td>
<td>0.018 52.5 43.4 17.8%</td>
</tr>
<tr>
<td>Coal Price = $1.5/GJ</td>
<td>0.008 1.702 1.442 13.5%</td>
<td>0.017 52.5 42.2 17.9%</td>
</tr>
<tr>
<td>FCF = 11%, CF = 85%</td>
<td>0.008 1.702 1.426 13.4%</td>
<td>0.016 52.5 41.0 18.0%</td>
</tr>
<tr>
<td><strong>Oxyfuel Sensitivity Case</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal Base Case Assumptions</td>
<td>0.007 2.417 2.201 9.0%</td>
<td>0.014 78.8 71.2 8.3%</td>
</tr>
<tr>
<td>Learning Starts with First Plant</td>
<td>0.011 2.417 2.150 10.2%</td>
<td>0.020 78.8 73.6 9.3%</td>
</tr>
<tr>
<td>Current Capture Capacity = 0 GW</td>
<td>0.010 2.417 2.121 10.7%</td>
<td>0.019 78.8 76.0 9.6%</td>
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<tr>
<td>Non-CSS Exp. Multipliers = 2.0</td>
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<td>Coal Price = $1.5/GJ</td>
<td>0.008 2.417 2.051 11.6%</td>
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<td>0.007 2.417 2.020 11.6%</td>
<td>0.016 78.8 83.4 10.3%</td>
</tr>
</tbody>
</table>

#### Diagrams

- **COST OF ELECTRICITY (excluding T&S costs)**
- **Percent Reduction in COE**

**B.S. Rubin, Carnegie Mellon**

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E.S. Rubin, Carnegie Mellon
Conclusions from These Studies

- Future costs of power plants with CO₂ capture can be reduced significantly
- IGCC plants have potential for larger cost reductions than combustion-based plants (esp. from economies of scale)
- Achieving future cost reductions will require not only sustained R&D, but also large-scale deployment to foster learning-by-doing

What is needed to realize improved technology?
Barriers to CCS Deployment

- No current policy mandate or strong incentives for large reductions in CO₂ emissions
- No experience in large-scale power plant applications
- High cost of current CCS technologies
- Lack of a regulatory framework for large-scale geological sequestration projects
- Unresolved legal issues related to sub-surface property rights and long-term liabilities
- Uncertainties about public acceptance

Full-Scale CCS Projects Are Urgently Needed

- To establish the reliability and true cost of CCS, esp. in utility applications at commercial scale, for:
  - Alternative technologies (PC, IGCC; new, retrofit)
  - Different coal types (bituminous, sub-bit, lignite)
  - Different geological settings
- To help resolve the legal and regulatory issues of large-scale geological sequestration
- To begin reducing future costs of CCS (via learning-by-doing together with sustained R&D)

~10 full-scale projects are needed
Will CCS Be Used to Mitigate Climate Change?

- We are likely to see several successful demonstrations of CCS technology in next 5-10 yrs, but …
- Widespread CCS deployment will not occur without a sufficiently strong climate policy driver

Thank You

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