The Economics of CO₂ Capture for Enhanced Oil Recovery and Climate Change Mitigation

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Outline of Talk

• Status of CO₂ capture technology
• Opportunities for enhanced oil recovery
• The costs of CO₂ captured and avoided
• The outlook for advanced capture systems
• Challenges moving forward

Many Ways to Capture CO₂

Status of CO₂ capture technology

CO₂ Separation and Capture

Absorption
Adsorption
Pyrolysis
Cryogenics
Membranes
Microbial/Algal Systems

Choice of technology depends strongly on application
Leading Candidates for CCUS

• Large industrial sources of CO₂ such as:
  • Gas processing, refineries, petrochemical plants
  • Hydrogen and ammonia production plants
  • Pulp and paper plants
  • Cement plants

• Fossil fuel power plants
  • Pulverized coal combustion (PC)
  • Natural gas combined cycle (NGCC)
  • Integrated coal gasification combined cycle (IGCC)

For these applications, various stages of technology development

• Commercial use
• Full-scale demonstration plant
• Pilot plant scale
• Laboratory or bench scale
• Conceptual design

Commercial Post-Combustion Systems for Industrial CO₂ Capture

BP Natural Gas Processing Plant
(En-Salah, Algeria)

Source: IEA GHG, 2008

Post-Combustion CO₂ Capture at Coal-Fired Power Plants

Shady Point Power Plant
(Panama, Oklahoma, USA)

Source: ABB Lummus

Warrior Run Power Plant
(Cumberland, Maryland, USA)
Post-Combustion CO₂ Capture at a Gas-Fired Power Plant

Commercial Pre-Combustion CO₂ Capture Systems

DOE-Supported Demonstrations

<table>
<thead>
<tr>
<th>Performer</th>
<th>Capture Technology</th>
<th>Capture Rate (m tons/y)</th>
<th>Target Formation</th>
<th>Start Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRG Energy</td>
<td>Amine</td>
<td>~0.5</td>
<td>EOR</td>
<td>2015</td>
</tr>
<tr>
<td>FutureGen Alliance</td>
<td>Oxy</td>
<td>1.0</td>
<td>EOR/Saline</td>
<td>2015</td>
</tr>
<tr>
<td>Summit Texas Clean Energy</td>
<td>Solecil</td>
<td>3.0</td>
<td>EOR</td>
<td>2014</td>
</tr>
<tr>
<td>Southern Company</td>
<td>Solecil</td>
<td>2.0</td>
<td>EOR</td>
<td>2014</td>
</tr>
<tr>
<td>Hydrogen Energy California</td>
<td>Rectisol</td>
<td>2.0</td>
<td>EOR/Saline</td>
<td>2016</td>
</tr>
<tr>
<td>Leucadia Energy Lake Charles</td>
<td>Rectisol</td>
<td>4.0</td>
<td>EOR</td>
<td>2014</td>
</tr>
<tr>
<td>Air Products</td>
<td>Amine</td>
<td>1.0</td>
<td>EOR</td>
<td>2013</td>
</tr>
<tr>
<td>Archer Daniels Midland</td>
<td>Amine</td>
<td>1.0</td>
<td>Saline</td>
<td>2014</td>
</tr>
</tbody>
</table>

Can EOR Stimulate Capture Technology Deployment?

- What is the outlook for EOR production?
- What is the economic value of CO₂ for EOR?
- What is the availability and cost of providing CO₂ from various sources?
- Is there a significant role for power plants?
- In the context of climate change mitigation, is CO₂-EOR a safe and secure method of carbon sequestration?
Growth of CO₂-EOR Production in the United States

Significant further growth is constrained by lack of CO₂ supplies

Sources of CO₂ Supply for EOR Operations in the U.S.

CO₂ Sources for EOR Floods

NETL/ARI CO₂ EOR Resource Assessment

- Field-to-field stream tube simulations of CO₂ EOR floods (CO₂ PROPHET)
- Screen for depth, crude gravity, and size
- Determine miscible/immiscible
- Economics based on 40 $/mtCO₂ cost, 85 $/bbl crude oil, 20% IRR

CO₂ EOR Resource Assessment Results: Lower 48 Onshore, Economically Recoverable

<table>
<thead>
<tr>
<th>Crude Oil Production, Bbls</th>
<th>CO₂ Demand, Bbls</th>
<th>Average Efficiency of CO₂ Use (Bbls/mt CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Best Practices</td>
<td>24</td>
<td>9</td>
</tr>
<tr>
<td>Next Generation CO₂ EOR technology</td>
<td>60</td>
<td>17</td>
</tr>
</tbody>
</table>
**Future CO₂ Supply Scenario**
(Based on Best Current Practices for CO₂-EOR Technologies)

- 24 billion bbl of CO₂-EOR resources
- 9 B mt CO₂ demand
- 5.5 MMmt CO₂/yr growth in CO₂ demand
- 46 MMmtCO₂/yr from industrial vents
- Peak dilute sources is 156 MMmtCO₂/yr
- 45% of CO₂ from dilute sources

**Source:** P. DiPietro and C. Nichols, NETL, 2012

**Future CO₂ Supply Scenario**
(Based on “Next Generation” CO₂-EOR Technologies)

- 60 billion bbl of CO₂-EOR resources
- 17 B mt CO₂ demand
- 7 MMmt CO₂/yr growth in CO₂ demand
- 46 MMmtCO₂/yr from industrial vents
- Peak dilute sources is 214 MMmtCO₂/yr
- 63% of CO₂ from dilute sources

**Source:** P. DiPietro and C. Nichols, NETL, 2012

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**Future EOR Production Scenario**
(Based on “Next Generation” CO₂-EOR Technologies)

- Significant improvements to today’s technology
- Application to residual oil zones (ROZs)
- Integration of CO₂-EOR and CO₂ storage
- Advanced near-miscible/immiscible technology
- Deployment in offshore oil fields and Alaska

**Source:** V. Kuuskraa, ARI, 2011 and P. DiPietro, NETL, 2012

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**The costs of capturing and sequestering CO₂**
Many Recent CCS Cost Studies

- 2005: IPCC Special Report on CCS
- 2007: EPRI Report No. 1014223
- 2007: MIT Future of Coal Report
- 2008: EPRI Report No. 1018329
- 2009: Chen & Rubin, Energy Policy
- 2009: ENCAP Report D.1.2.6
- 2009: EPRI Report No. 1017495
- 2010: Carnegie Mellon IECM v. 6.4
- 2010: UK DECC, Most MacDonald Report
- 2010: Kheshgiri, et al., SPE 139716-PP
- 2010: DOE/NETL Report 2010/1397
- 2010: DOE EIA Cost Update Report
- 2011: OECD/IEA Working Paper
- 2011: Global CCS Institute Update

My Observations

- Despite many recent studies on the cost of CO₂ capture and storage (CCS) there remain significant differences in underlying costing methods (as well as key assumptions) that are often not readily apparent.
- Such differences contribute to significant confusion, misunderstanding and (in some cases) the mis-representation of CO₂ abatement costs, especially among audiences unfamiliar with details of CCS costing.

Audiences for (and Sources of) Cost Estimates

**Government**
- Policymakers
- Analysts
- Regulators
- R&D agencies

**Industry**
- Operators
- Vendors
- A&E firms
- Venture capital
- Tech developers
- R&D orgs

**NGOs**
- Environmental
- Media
- Academia
- Foundations

Source: Based on Herzog, 2011

A Hierarchy of Methods to Estimate CCUS Costs

- Ask an expert
- Use published values
- Modify published values
- Derive new results from a model
- Commission a detailed engineering study
Common Measures of CCS Cost

- Cost of CO\(_2\) avoided
- Cost of CO\(_2\) captured
- Increased capital cost
- Increased cost of electricity

Cost of CO\(_2\) Avoided

\[
\text{Cost of CO}_2 \text{ Avoided} = \frac{(S/\text{MWh})_{\text{ccs}} - (S/\text{MWh})_{\text{ref}}}{(t \text{ CO}_2/\text{MWh})_{\text{ref}} - (t \text{ CO}_2/\text{MWh})_{\text{ccs}}} \times (\text{s/t CO}_2)
\]

- This widely used metric gives the cost of reducing a ton of CO\(_2\) emissions while still providing a unit of useful product (e.g., a MWh of delivered electricity)
- It should (but often does not) include the full chain of CCS processes, i.e., capture, transport and storage (emissions are not avoided until sequestered)
- It is a relative cost measure that is very sensitive to the choice of reference plant without CCS

Dollars per Ton

- This is the metric most commonly used in technical and policy forums to quantify the cost of CCS (as well as other methods of reducing carbon emissions)
- Also the measure that is most easily misunderstood and misapplied

Cost of CO\(_2\) avoided is sensitive to assumed reference plant w/o CCS

Different questions require different reference plants

Cost and emissions data from NETL, 2010

$106/t CO_2 avoided

$41/t CO_2 avoided

$106/t CO_2 avoided

$41/t CO_2 avoided

\(\Delta \text{COE}_{ccs-ref} = 34 \text{ S/MWh}\)
Two Additional Measures — Same Units, Different Meanings

- **Cost of CO₂ Avoided ($/t CO₂)**
  \[
  \frac{(\$/MWh)_{ccs} - (\$/MWh)_{reference}}{(t\ CO₂/MWh)_{ccs, produced} - (t\ CO₂/MWh)_{ccs}}
  \]

- **Cost of CO₂ Captured ($/t CO₂)**
  \[
  \frac{(\$/MWh)_{ccs} - (\$/MWh)_{reference}}{(t\ CO₂/MWh)_{ccs, produced} - (t\ CO₂/MWh)_{ccs}}
  \]

- **Cost of CO₂ Abated (Reduced) ($/t CO₂)**
  \[
  \frac{(\$/NPV)_{ccs} - (\$/NPV)_{reference}}{(t\ CO₂)_{ccs} - (t\ CO₂)_{reference}}
  \]

*Use with caution!*

Cost of Electricity (COE)

\[
\text{COE ($/MWh)} = \frac{\text{TCC}(\text{FCF}) + \text{FOM}}{(\text{CF})(8760)(\text{MW})} + \text{VOM} + (\text{HR})(\text{FC})
\]

- **TCC** = Total capital cost ($)
- **FCF** = Fixed charge factor (fraction)
- **FOM** = Fixed operating & maintenance costs ($/yr)
- **VOM** = Variable O&M costs, excluding fuel cost ($/MWh)
- **HR** = Power plant heat rate (MJ/MWh)
- **FC** = Unit fuel cost ($/MJ)
- **CF** = Annual average capacity factor (fraction)
- **MW** = Net power plant capacity (MW)

Increase in COE

- A common metric for power plant CCS cost
- Typically reported on a “levelized” basis (LCOE)
  - Implies that all parameters in the COE equation (including FCF and CF) reflect their levelized value over the life of the plant
  - Most studies report LCOE in constant dollars (no inflation effects); some report in current (nominal) dollars, which yield higher values
  - O&M costs are multiplied by a “levelization factor” calculated from specified rates of inflation and real cost escalations over the plant life.

Many Factors Affect CCS Costs

- **Choice of Power Plant and CCS Technology**
- **Process Design and Operating Variables**
- **Economic and Financial Parameters**
- **Choice of System Boundaries; e.g.,**
  - One facility vs. multi-plant system (regional, national, global)
  - GHG gases considered (CO₂ only vs. all GHGs)
  - Power plant only vs. partial or complete life cycle
- **Time Frame of Interest**
  - First-of-a-kind plant vs. nth plant
  - Current technology vs. future systems
  - Consideration of technological “learning”
Ten Ways to Reduce CCUS Costs

10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel cost
7. Assume high EOR credits for CO₂ stored
6. Omit certain capital costs
5. Report $/ton CO₂ based on short tons
4. Assume long plant lifetime
3. Assume low interest rate (discount rate)
2. Assume high plant utilization (capacity factor)
1. Assume all of the above!

...and we have not yet considered the CCS technology!

Capital Cost Elements (Recent Studies)

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Process facility capital</td>
<td>Bare basket (BC)</td>
<td>Bare basket cost (BEC)</td>
<td>Cost structure/interest &amp; insurance</td>
</tr>
<tr>
<td>General facilities capital</td>
<td>Engineering &amp; Office Fees</td>
<td>Engineering &amp; office fees</td>
<td>Mechanical, Equip. &amp; installation</td>
</tr>
<tr>
<td>Contingencies-project and process</td>
<td>Project Contingency Cost</td>
<td>Project contingency cost</td>
<td>Project indirects</td>
</tr>
<tr>
<td>Total plant cost</td>
<td>Total plant cost (TPC)</td>
<td>Total plant cost (TPC)</td>
<td>Total cost before contingency and fee</td>
</tr>
<tr>
<td>Variable O&amp;M</td>
<td>Pre-production costs</td>
<td>Total O&amp;M</td>
<td>Total O&amp;M</td>
</tr>
<tr>
<td>Total plant investment (TP)</td>
<td>Total plant investment (TP)</td>
<td>Total Project EPC</td>
<td></td>
</tr>
<tr>
<td>Owner's costs</td>
<td>Owner's costs (before project financing)</td>
<td></td>
<td>Owner's costs (before project financing)</td>
</tr>
<tr>
<td>Total Capital Requirement (TCR)</td>
<td>Total Capital Requirement (TCR)</td>
<td>Total Capital Requirement (TCR)</td>
<td>Total Capital Requirement (TCR)</td>
</tr>
</tbody>
</table>

O&M Cost Elements in Recent Studies

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>Operating labor</td>
<td>Operating labor</td>
<td>Operating labor</td>
</tr>
<tr>
<td>Indirects</td>
<td>Maintenance labor</td>
<td>Maintenance labor</td>
<td>Maintenace labor</td>
</tr>
<tr>
<td>Contingencies</td>
<td>Property taxes and insurance</td>
<td>Property taxes and insurance</td>
<td>Property taxes and insurance</td>
</tr>
<tr>
<td>Total O&amp;M</td>
<td>Non-product revenue</td>
<td>Total O&amp;M</td>
<td>Total O&amp;M</td>
</tr>
<tr>
<td>Other costs</td>
<td>Contingencies</td>
<td>Other costs</td>
<td>Contingencies</td>
</tr>
<tr>
<td>Total Capital Requirement (TCR)</td>
<td>Total Capital Requirement (TCR)</td>
<td>Total Capital Requirement (TCR)</td>
<td>Total Capital Requirement (TCR)</td>
</tr>
</tbody>
</table>

Current Status of Costing Methods

- Various organizations have developed detailed procedures and guidelines for calculating power plant and CCS costs (capital, O&M, COE)
- Across different organizations, however, there are significant differences and inconsistencies in the costing methods that are used

No consistent set of cost categories or nomenclature across studies
Elements of “Owner’s Costs” in Several Recent Studies

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Preproduction (Start-Up) costs</td>
<td>(None)</td>
<td>Preproduction (Start-Up) costs</td>
<td>Feasibility studies</td>
<td>(None)</td>
<td>Preproduction (Start-Up) costs</td>
</tr>
<tr>
<td>Working capital</td>
<td>Prepaid royalties</td>
<td>Obtaining permits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inventory capital</td>
<td>Inventory capital</td>
<td>Arranging financing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Financing cost</td>
<td>Initial catalyst/chem.</td>
<td>Other misc. costs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Land</td>
<td>Land</td>
<td>Land purchase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>Other</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

No consistent set of cost categories or nomenclature across studies

Key Assumptions Also Vary Across Studies

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Size (PC case)</td>
<td>550 MW (net)</td>
<td>550 MW (net)</td>
<td>750 MW (net)</td>
<td>800 MW (net)</td>
<td>1600 MW (gross)</td>
</tr>
<tr>
<td>Capacity Factor</td>
<td>85%</td>
<td>85%</td>
<td>85%</td>
<td>85% (up to 85%)</td>
<td>Series yearly</td>
</tr>
<tr>
<td>Constant/Current ($)</td>
<td>Current</td>
<td>Current</td>
<td>Current</td>
<td>Current</td>
<td>Current</td>
</tr>
<tr>
<td>Discount Rate</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Plant Book Life (yr)</td>
<td>20</td>
<td>30</td>
<td>30</td>
<td>25</td>
<td>32-40 (FOAK)</td>
</tr>
<tr>
<td>Capital Charge Factor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>35-61 (NEAK)</td>
</tr>
<tr>
<td>Capital Charge Factor</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>35-61 (NEAK)</td>
</tr>
<tr>
<td>Levelization Factor</td>
<td>no CCS</td>
<td>1.1566</td>
<td>1.116</td>
<td>1.121</td>
<td>N/A</td>
</tr>
<tr>
<td>w/ CCS</td>
<td>0.175</td>
<td>0.124</td>
<td>0.121</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Outside Cost Levelization Factor</td>
<td>no CCS</td>
<td>1.2676</td>
<td>1.00</td>
<td>1.00</td>
<td>N/A</td>
</tr>
<tr>
<td>w/ CCS</td>
<td>1.2676</td>
<td>1.00</td>
<td>1.00</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Transparency is critical for understanding

Uncertainty, Variability & Bias

- Variability and uncertainty can (in principle) be accounted for in costing methods, e.g., via parametric (sensitivity) analysis, choice of parameter values, and/or probabilistic analysis
- Bias can arise in project design specifications and choice of parameters and values for cost estimates
  - Can be difficult to detect or prove
  - Independent (3rd party) evaluations can be helpful

The Devil is in the Details

- Need to improve the consistency, reporting and transparency of costing methods and assumptions to enhance the understanding of CCS costs

Especially important for evaluating new or emerging technologies
A CCS Cost Task Force has recommended a path forward

White Paper Contents:
- Defining Project Scope and Design
- Defining Nomenclature and Cost Categories for CCS Cost Estimates
- Quantifying Elements of CCS Cost
- Defining Financial Structure and Economic Assumptions
- Calculating the Costs of Electricity and CO₂ Avoided
- Guidelines for CCS Cost Reporting

Geological Storage of Captured CO₂ with Enhanced Oil Recovery (EOR)

Illustrative Cases Studies
- Use the IECM to analyze effect on overall plant cost of varying the price of CO₂ sold for EOR for three plant types:
  - PC Plant
  - NGCC Plant
  - IGCC Plant
The Integrated Environmental Control Model (IECM)

- A desktop/laptop computer simulation model developed for DOE/NETL
- 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)
- Free and publicly available at: www.iecm-online.com

Illustrative Cases Studies (I)

<table>
<thead>
<tr>
<th>Plant Type</th>
<th>Supercritical PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal Type</td>
<td>Illinois bituminous</td>
</tr>
<tr>
<td>Net Plant Capacity (Ref / CCS)</td>
<td>550 MW / 550 MW</td>
</tr>
<tr>
<td>CO₂ Capture System</td>
<td>Econamine FG+</td>
</tr>
<tr>
<td>Capacity Factor (levelized)</td>
<td>75%</td>
</tr>
<tr>
<td>Fixed Charge Factor (const $ / current $)</td>
<td>0.113 / 0.147</td>
</tr>
</tbody>
</table>

LCOE vs. CO₂ EOR Price (SCPC Plant)

Avoidance Cost vs. CO₂ Price (SCPC Plant)
Illustrative Cases Studies (2)

<table>
<thead>
<tr>
<th>Plant Type</th>
<th>NGCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas Turbine Type</td>
<td>GE 7FB</td>
</tr>
<tr>
<td>Net Plant Capacity (Ref / CCS)</td>
<td>323 MW / 455 MW</td>
</tr>
<tr>
<td>CO₂ Capture System</td>
<td>Econamine FG+</td>
</tr>
<tr>
<td>Capacity Factor (levelized)</td>
<td>75%</td>
</tr>
<tr>
<td>Fixed Charge Factor (const $ / current $)</td>
<td>0.113 / 0.147</td>
</tr>
</tbody>
</table>

SCPC vs. NGCC

<table>
<thead>
<tr>
<th>CO₂ Price for EOR ($/tonne CO₂)</th>
<th>LCOE (constant 2010 $/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>90</td>
</tr>
<tr>
<td>20</td>
<td>80</td>
</tr>
<tr>
<td>30</td>
<td>70</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
</tr>
</tbody>
</table>

Sensitivity Cases

<table>
<thead>
<tr>
<th>Case</th>
<th>LCOE (SCPC-CCS)</th>
<th>Avoidance Cost ($/t)</th>
<th>Cost of Capture ($/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base CCS - constant $</td>
<td>101</td>
<td>59</td>
<td>36</td>
</tr>
<tr>
<td>current $, 3% inflation</td>
<td>134</td>
<td>78</td>
<td>47</td>
</tr>
<tr>
<td>+discount rate = 20%</td>
<td>143</td>
<td>84</td>
<td>51</td>
</tr>
<tr>
<td>+discount rate = 30%</td>
<td>154</td>
<td>90</td>
<td>54</td>
</tr>
</tbody>
</table>

What is the potential for advanced capture technology?

Many other parameters can affect these results
Better Capture Technologies Are Emerging

- Post-combustion (existing, new PC)
- Pre-combustion (IGCC)
- Oxycombustion (new PC)
- CO₂ compression (all)
- Advanced physical solvents
- Solid sorbents
- Membrane systems
- ITMs
- Biomass cofiring
- Ammonia
- Advanced amine solvents
- Chemical looping
- OTM boiler
- Biological processes
- CAR process

Time to Commercialization

Present 5+ years 10+ years 15+ years 20+ years

Two Approaches to Estimating Potential Cost Savings

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

Potential Cost Reductions Based on Engineering-Economic Analysis

Source: DOE/NETL, 2006
**Potential Cost Reductions Based on Engineering-Economic Analysis**

- **IGCC Technologies**
  - No CCS: $155$/MWh
  - CCS with No R&D: $140$/MWh
  - CCS with R&D: $120$/MWh
- **Pulverized Coal Technologies**
  - No CCS: $160$/MWh
  - CCS with No R&D: $150$/MWh
  - CCS with R&D: $130$/MWh

- 31% reduction for CCS with R&D
- 29% above no CCS

Source: DOE/NETL, 2010

---

**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

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**Empirical “Learning Curves”**

- Cost trends modeled as a log-linear relationship between unit cost and cumulative production or capacity: $y = ax^{-b}$

- Case studies used for power plant components:
  - Fine 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)

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**Projected Cost Reductions for Power Plants with CO₂ Capture**

- (after 100 GW of cumulative CCS capacity worldwide)

- **Plant-level learning curves developed from component-level analyses**

- **Upper bound of ranges are similar to estimates from “bottom-up” analyses**

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Conclusions

• Significant potential to reduce the cost of carbon capture via:
  • New or improved CO₂ capture technologies
  • Improved plant efficiency and utilization

Challenges for advanced CCS technology

Most New Capture Concepts Are Far from Commercial Availability

Typical Cost Trend for a New Technology

Source: NASA, 2009
Source: EPRI, 2008. ——
Most new concepts take decades to commercialize...many never make it

Development timelines for three novel processes for combined SO₂–NOₓ capture

The CCSI Initiative to Accelerate New Capture Systems

The Critical Role of Policy

- The pace and direction of innovations in carbon capture technology will be strongly influenced by climate and energy policies—and their role in establishing markets for CCUS technologies
Thank You

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