The Outlook for Advanced Carbon Capture Technology

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Outline of Talk

• Why the interest in carbon capture?
• Status of current technology
• Opportunities for advanced technology
• Challenges for advanced carbon capture
Why the interest in carbon capture?
Drivers of Global Climate Change

- Concentrations of greenhouse gases in the atmosphere are rising sharply due to GHG emissions from human activities.
- The resulting heat-trapping effect leads to climate change on a global scale.

Source: IPCC, 2001
The Climate Change Policy Driver

• 1992 U.N. Framework Convention on Climate Change called for “stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”
Stabilization Requires Large Emission Reductions, Soon

Recent assessments indicate potentially serious impacts for more that a 2°C rise in average global temperature

<table>
<thead>
<tr>
<th>Required change in global CO$_2$, equiv emissions from 2000 to 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>–85% to –50%</td>
</tr>
</tbody>
</table>

Source: IPCC, 2007

Stabilizing climate change will require urgent action

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**CO₂ from Energy Use is the Dominant Greenhouse Gas**

**U.S. Greenhouse Gas Emissions**
weighted by 100-yr Global Warming Potential (GWP)

- **CO₂**: 83.9%
- **CH₄**: 6.5%
- **N₂O**: 2.2%
- **Others**: 7.4%

*Source: USEPA, 2007*
Sources of CO₂ Emissions

U.S. CO₂ Emissions

(a) End-Use Energy Sectors

- Residential: 20.1%
- Commercial: 17.1%
- Industrial: 29.8%
- Transportation: 33.0%

(b) Electric Power Sector

- Percent of U.S. CO₂ Emissions: 39.8%

Source: Based on USDOE, 2008

Electricity + Vehicles emit ≈ 75% of all CO₂

Fossil fuels = 40% of CO₂ and 70% of U.S. electricity

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Motivation for Carbon Capture and Storage (CCS)

- Fossil fuels will continue to be used for many decades —alternatives not able to substitute quickly
- CCS is the ONLY way to get large CO$_2$ reductions from fossil fuel use—a potential bridging strategy
- CCS can also help decarbonize the transportation sector via low-carbon electricity and hydrogen from fossil fuels
- Energy-economic models show that without CCS, the cost of mitigating climate change will be much higher
Status of CCS technology
Schematic of a CCS System

Carbonaceous Fuels

Air or Oxygen

Power Plant or Industrial Process

CO₂ Capture & Compress

CO₂ Transport

CO₂ Storage (Sequestration)

Useful Products
(Electricity, Fuels, Chemicals, Hydrogen)

- Post-combustion
- Pre-combustion
- Oxyfuel combustion

- Pipeline
- Tanker

- Depleted oil/gas fields
- Deep saline formations
- Unmineable coal seams
- Ocean
- Mineralization
- Reuse

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Leading Candidates for CCS

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

• Other large industrial sources of CO₂ such as:
  ▪ Refineries, fuel processing, and petrochemical plants
  ▪ Hydrogen and ammonia production plants
  ▪ Pulp and paper plants
  ▪ Cement plants

— Main focus is on power plants, the dominant source of CO₂ —
Many Ways to Capture CO$_2$

**CO2 Separation and Capture**

- **Absorption**
  - Chemical
    - MEA
    - Caustic
    - Other
  - Physical
    - Selexol
    - Rectisol
    - Other

- **Adsorption**
  - Adsorber Beds
    - Alumina
    - Zeolite
    - Activated C
  - Regeneration Method
    - Pressure Swing
    - Temperature Swing
    - Washing

- **Cryogenics**

- **Membranes**
  - Gas Separation
    - Polyphenyleneoxide
    - Polydimethylsiloxane
  - Gas Absorption
    - Polypropylene
  - Ceramic Based Systems

- **Microbial/Algal Systems**

*Choice of technology depends strongly on application*

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CO₂ Capture Options for Power Plants: Post-Combustion Capture

Steam Turbine Generator

PC Boiler

Air Pollution Control Systems (NOₓ, PM, SO₂)

CO₂ Capture

Amine/CO₂ Separation

CO₂ Compression

Flue gas to atmosphere

Coal

Air

Steam

Electricity

Also for NGCC plants
CO₂ Capture Options for Power Plants: Oxy-Combustion Capture

- PC Boiler
- Air Pollution Control Systems (NOₓ, PM, SO₂)
- Distillation System
- CO₂ Compression
- CO₂ to storage
- To atmosphere
- Steam Turbine Generator
- Electricity
- CO₂ to recycle
- Air Separation Unit
- Steam
- Coal
- O₂
- CO₂
- H₂O
CO₂ Capture Options for Power Plants: Pre-Combustion Capture

Air Separation Unit

Gasifier

Quench System

Shift Reactor

Sulfur Removal

CO₂ Capture

Selexol/CO₂ Separation

CO₂ Compression

Combined Cycle Power Plant

Flue gas to atmosphere

Electricity to atmosphere

CO₂ to storage

Coal

H₂O

O₂

Air

H₂O

H₂
Pre- and post-combustion CO₂ capture technologies are commercial and widely used in industrial processes; also at several gas-fired and coal-fired power plants, at small scale; CO₂ capture efficiencies are typically 85-90%. Oxyfuel capture is still under development.

CO₂ transport via pipelines is a mature technology.

Geological storage of CO₂ is commercial on a limited basis, mainly for EOR; several projects in deep saline formations are operating at scales of ~1 Mt CO₂ /yr.

Large-scale integration of CO₂ capture, transport and geological sequestration has been demonstrated at several industrial sites (outside the U.S.) — but not yet at an electric power plant at full-scale.
Examples of Pre-Combustion CO₂ Capture Systems

Petcoke Gasification to Produce H₂
*Coffeyville, Kansas, USA*

Coal Gasification to Produce SNG
*Beulah, North Dakota, USA*

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Pre-Combustion Capture at IGCC Plants

Puertollano IGCC Plant (Spain)

Buggenhun IGCC Plant (The Netherlands)

Source: Elcano, 2007
Source: Nuon, 2009

Pilot plants under construction at two IGCC plants (startup expected in late 2010)
Post-Combustion Technology for Industrial CO$_2$ Capture

BP Natural Gas Processing Plant
(In Salah, Algeria)

Source: IEA GHG, 2008

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Examples of Post-Combustion CO₂ Capture at U.S. Power Plants

Gas-fired

Bellingham Cogeneration Plant
(Bellingham, Massachusetts, USA)

Coal-fired

Warrior Run Power Plant
(Cumberland, Maryland, USA)

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Oxy-Combustion CO$_2$ Capture from a Coal-Fired Boiler

30 MW$_t$ Pilot Plant (~10 MW$_e$) at Vattenfall Schwarze Pumpe Station (Germany)

Source: Vattenfall, 2008

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CO$_2$ Pipelines in the United States

~3600 miles of pipeline
~50 MtCO$_2$/yr transported

Source: USDOE/Battelle

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Source: NRDC
### Large-Scale CCS Projects Now Operating

<table>
<thead>
<tr>
<th>Project</th>
<th>Operator</th>
<th>Geological Reservoir</th>
<th>Injection Start Date</th>
<th>Injection Rate (MtCO₂/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleipner (Norway)</td>
<td>StatoilHydro</td>
<td>Saline Formation</td>
<td>1996</td>
<td>1.0</td>
</tr>
<tr>
<td>Weyburn (Canada)</td>
<td>EnCana</td>
<td>Oil Field (EOR)</td>
<td>2000</td>
<td>1.2*</td>
</tr>
<tr>
<td>In Salah (Algeria)</td>
<td>Sonatrach, BP, StatoilHydro</td>
<td>Depleted Gas Field</td>
<td>2004</td>
<td>1.2</td>
</tr>
<tr>
<td>Snohvit (Norway)</td>
<td>StatoilHydro</td>
<td>Saline Formation</td>
<td>2008</td>
<td>0.7</td>
</tr>
</tbody>
</table>

* Average rate over 15 year contract. Recent expansion to ~3 Mt/yr for Weyburn + Midale field.
Geological Storage of Captured CO$_2$ in a Deep Saline Formation

Sleipner Project
(Norway)

Source: Statoil
Geological Storage of Captured CO₂ in a Deep Saline Formation

Snohvit LNG Project (Norway)

Source: www.Snohvit, 2009

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Geological Storage of Captured CO$_2$ in a Depleted Gas Formation

In Salah /Krechba  (Algeria)
Geological Formations in North America

Oil & Gas Fields

Deep Saline Formations

Source: NETL, 2009

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

Weyburn Field, Canada

Dakota Coal Gasification Plant, ND

Sources: IEAGHG; NRDC; USDOE

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CCS at a Coal-Fired Power Plant with Storage in a Deep Saline Formation

(Pilot plant scale)

20 MW capture unit at AEP’s Mountaineer Power Plant
(West Virginia)

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Source: AEP, 2009
Still Missing

- Full-scale power plant demo #1
- Full-scale power plant demo #2
- Full-scale power plant demo #3
- Full-scale power plant demo #4
- Full-scale power plant demo #5
- Full-scale power plant demo #6
- Full-scale power plant demo #7
- Full-scale power plant demo #8
- Full-scale power plant demo #9
- Full-scale power plant demo #10
Full-Scale Demonstration Projects Are Urgently Needed to . . .

- Establish the **reliability, safety** and true **cost** of CCS in full-scale power plant applications
- Help resolve legal and regulatory issues regarding geological sequestration
- Help address issues of public acceptance
- Begin reducing future costs via learning-by-doing

- **Cost per project ≈ $1 billion** (install/operate CCS, 400 MW, 5 yrs)

**Financing large-scale projects has been a major hurdle**
Many projects are planned or underway at various scales

- Map shows operating plus proposed or planned projects in the U.S. and Canada. They encompass power plants, industrial sources and research projects spanning a large range of scale.

Source: DOE, 2009
Substantial CCS Activity Globally

Source: DOE, 2009
Roadmaps for CCS Deployment

**DOE Roadmap**
- Capture Technology Laboratory-Bench-Pilot Scale R&D
- Capture Technology Large-Scale Field Testing
- Carbon Sequestration Phase II -- Validation
- Carbon Sequestration Phase III -- Deployment
- Capture Technology Full-Scale Demos
- CCS Commercialization

**EPRI Roadmap**
- Pilots
  - Chilled Ammonia Pilot
  - Other Pilots (Post-Combustion and Oxy-Combustion)
- Demonstration
  - IGCC + CCS Projects
  - UltraGen Projects
  - Other Projects (Oxy-Combustion)
- Integration
  - AEP Mountaineer
  - Southern/SSEI Fm. III
  - Other Demonstrations
- Timing Dictates Pilots and Demonstrations be Performed in Parallel

*Figure 6-1*
Steps in Technology Validation and Scale-Up Projects to Meet CURC-EPRI Roadmap Goals for Advanced Coal Technologies with CCS

Commercialization expected by 2020

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The cost of CCS
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”
Common Measures of Cost

- Cost of Electricity (COE) ($/MWh)
  
  \[
  \frac{(TCC)(FCF) + FOM}{(CF)(8760)(MW)} + VOM + (HR)(FC)
  \]

- Cost of CO₂ Avoided ($/ton CO₂ avoided)
  
  \[
  \frac{(\$/MWh)_{ccs} - (\$/MWh)_{reference}}{(CO₂/MWh)_{ref} - (CO₂/MWh)_{ccs}}
  \]

Also:
- Cost of CO₂ Captured ($/ton CO₂ captured)
- Cost of CO₂ Reduced/Abated ($/ton CO₂ abated)
Ten Ways to Reduce Estimated Cost

(inspired by D. Letterman)

10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel cost
7. Assume EOR credits for CO$_2$ storage
6. Omit certain capital costs
5. Report $/ton CO$_2$ 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!
Estimated Cost of New Power Plants with and without CCS

* 2007 costs for bituminous coals; gas price ≈ $4–7/GJ; 90% capture; aquifer storage
### Incremental Cost of CCS for New Power Plants Using Current Technology

**Increase in levelized cost for 90% capture**

<table>
<thead>
<tr>
<th>Incremental Cost of CCS relative to same plant type without CCS based on bituminous coals</th>
<th>Supercritical Pulverized Coal Plant</th>
<th>Integrated Gasification Combined Cycle Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increases in capital cost ($/kW) and generation cost ($/kWh)</td>
<td>~ 60–80%</td>
<td>~ 30–50%</td>
</tr>
</tbody>
</table>

The added cost to consumers due to CCS will be much smaller, reflecting the number and type of CCS plants in the generation mix at any given time.
## Typical Cost of CO₂ Avoided

(Relative to a new SCPC reference plant; bituminous coals)

<table>
<thead>
<tr>
<th>Power Plant System</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 ±$15/t</td>
<td>~ $50 /tCO₂ ±$10/t</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

• Costs to retrofit existing plants could be much higher
• Capture accounts for most (~80%) of the total cost
High capture energy requirements is a major factor in high CCS costs

<table>
<thead>
<tr>
<th>Power Plant Type</th>
<th>Added fuel input (%) per net kWh output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Existing subcritical PC</td>
<td>~40%</td>
</tr>
<tr>
<td>New supercritical PC</td>
<td>25-30%</td>
</tr>
<tr>
<td>New coal gasification (IGCC)</td>
<td>15-20%</td>
</tr>
<tr>
<td>New natural gas (NGCC)</td>
<td>~15%</td>
</tr>
</tbody>
</table>

Changes in plant efficiency due to CCS energy requirements also affect plant-level pollutant emission rates (per MWh). A site-specific context is needed to evaluate the net impacts.
### Breakdown of “Energy Penalty” for CO₂ Capture (SCPC and IGCC)

<table>
<thead>
<tr>
<th>Component</th>
<th>Approx. % of Total Req’m’t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Energy</td>
<td>~60%</td>
</tr>
<tr>
<td>CO₂ Compression</td>
<td>~30%</td>
</tr>
<tr>
<td>Pumps, Fans, etc.</td>
<td>~10%</td>
</tr>
</tbody>
</table>
What is the potential for lower-cost capture technology?
Better Capture Technologies Are Emerging

- Post-combustion (existing, new PC)
- Pre-combustion (IGCC)
- Oxycombustion (new PC)
- CO₂ compression (all)

- Amine solvents
- Physical solvents
- Cryogenic oxygen

- Advanced physical solvents
- Advanced chemical solvents
- Ammonia
- CO₂ compression

- PBI membranes
- Solid sorbents
- Membrane systems
- ITMs
- Biomass cofiring

- Ionic liquids
- Metal organic frameworks
- Enzymatic membranes

- Chemical looping
- OTM boiler
- CAR process

Cost Reduction Benefit

Time to Commercialization

Present 5+ years 10+ years 15+ years 20+ years
Technical Challenges and Research Pathways for Advanced Capture Concepts

Critical Challenges:
- Parasitic load
- Cost-effective oxygen
- Energy-efficient capture processes
- Scale-up
- Application to existing fleet
- Integration with advanced fuel conversion systems

Research Pathways:
- Post-Combustion
- Pre-Combustion
- Oxygen Supply
- Oxy-Combustion

Cross Cut Pathways:
- Heat and pressure integration with base power plant
- CO₂ compression
- Co-sequestration
- O₂ quality (oxy- and post-combustion)
- CO₂ quality (permitting/transportation)
- Post combustion capture, CO₂ recycle to concentrate flue gas

Key:
- Commercially available
- Pilot Scale
- Laboratory scale/conceptual

Source: DOE/NETL, 2009
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

19% -28% reductions in COE w/ CCS
Potential Cost Reductions Based on Engineering-Economic Analysis

Source: DOE/NETL, 2008

Source: DOE/NETL, 2010

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Analyzing Options for Power Plants

(IECM: The Integrated Environmental Control Model)

- A desktop/laptop computer model developed for DOE/NETL; free and publicly available at: 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
  - CO$_2$ capture and storage options (pre- and post-combustion, oxy-combustion; transport, storage)
  - Major updates in late 2009 & 2010
Current IECM Developments

• Performance and Cost Models of Advanced CO$_2$ Capture Systems:
  ▪ Advanced liquid solvents  (Peter Versteeg)
  ▪ Solid sorbent systems  (Justin Glier)
  ▪ Membrane capture systems  (Haibo Zhai)
  ▪ Advanced oxy-combustion (Kyle Borgert)
  ▪ Chemical looping combustion  (Hari Mantripragada)

• International cost adjustment module  (Hana Gerbelova)
• Other model enhancements  (Karen Kietzke)
Two Approaches to Estimating Future Technology Costs

- **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

Source: IIASA, 1996
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 to estimate learning rates for power plant components:
  - 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)
Potential Cost Reductions Based on Learning Curve Analysis*

(after 100 GW of cumulative CCS capacity worldwide)

- Upper bound of projected cost reduction are similar to estimates from DOE’s “bottom-up” analyses

* Plant-level learning curves developed from component-level analyses for each system
## Projected Cost Reductions, 2001–2050
(Based on Learning Curves + Global Energy Model)

### Results for two policy scenarios, 2001–2050

<table>
<thead>
<tr>
<th>Power Plant System</th>
<th>Reduction in Cost of Electricity ($/MWh)</th>
<th>Reduction in Mitigation Cost ($/tCO₂ avoided)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGCC – CC</td>
<td>12% – 40%</td>
<td>13% – 60%</td>
</tr>
<tr>
<td>IGCC – CC</td>
<td>22% – 52%</td>
<td>19% – 58%</td>
</tr>
<tr>
<td>PC – CC</td>
<td>14% – 44%</td>
<td>19% – 62%</td>
</tr>
</tbody>
</table>

*Source: van den Broek, et al., 2009*
Most New Capture Concepts Are Far from Commercial Availability

Technology Readiness Levels

Post-Combustion Capture

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

Development timelines for three novel processes for combined SO$_2$–NO$_x$ capture:

**Electron Beam Process**
- 1961: Process described by Bureau of Mines
- 1967: Pilot-scale testing begins
- 1979: Development of process begins
- 1985: Pilot-scale tests carried out in Kentucky
- 2008: Paper on process presented at WEC forum in Romania

**Copper Oxide Process**
- 1967: Pilot-scale testing begins
- 1971: Test conducted in Netherlands
- 1977: Process used in plant in Chengdu, China
- 2002: Process used in plant in Beijing, China

**NOXSO Process**
- 1965: Construction of full scale test begins
- 1982: Pilot-scale tests carried out in Japan
- 1997: NOXSO Corporation declares bankruptcy
- 2000: NOXSO process cited in ACS paper, Last NOXSO patent awarded

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Challenge: Accelerate the Pace of Innovation

The Process of Technological Change

- Invention
- Innovation (new or better product)
- Adoption (limited use of early designs)
- Diffusion (improvement & widespread use)

R&D

Learning By Doing

Learning By Using
Accelerating Innovation Requires

• Closer coupling and interaction between R&D performers and technology developers /users

• Better methods to identify promising options, evaluate new processes /concepts, and reduce number and size of pilot and demonstration projects (e.g., via improved simulation methods)

• New models for organizing the research enterprise

• Substantial and sustained support for R&D

• Government policies that create and foster markets for CCS technologies
Conclusions

• While the challenges are significant, so too are the opportunities to reduce the cost of carbon capture via:
  ▪ New or improved CO$_2$ capture technologies
  ▪ Improved plant efficiency and utilization

• In turn, this can greatly reduce the costs (and thus increase the likelihood) of avoiding the most serious impacts of climate change

• So— an exciting time to be working on this problem!
Thank You

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