Research Needs for Carbon Capture and Mitigation

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Photo art: A. Benlow
Agenda

Extent and Sources of CO₂ Emissions

• Management & Capture
• Research Needs
U.S. Energy-Related Carbon Dioxide Emissions, 1980-2030
(million metric tons)

History

- 5,945 in 2005

Projections

- 6,214 in 2010
- 6,944 in 2020
- 7,950 in 2030

Carbon Dioxide Emission Intensity, 1980-2030
(metric tons per million 2000 dollars of GDP)

- 486 in 2010
- 407 in 2020
- 353 in 2030

History Projections

- 7,950 in 2030
- 353 in 2030

Annual Energy Outlook 2007
Carbon Dioxide Emissions

billion metric tons

2005 2010 2020 2030

Low Growth

Reference

High Growth

Electric Power

Transportation

Industrial

Commercial

Residential

Annual Energy Outlook 2007
Needed: 1,300 New Power Plants

A Conservative Estimate

Nationally Important to Make Right Choices for Infrastructure Investments With 50+ Year Lifetime

Source: EIA/DOE
U.S. Electricity Generation Capacity Additions by Fuel, 2006-2030 (gigawatts)

- **Natural Gas**
- **Coal**
- **Renewables**
- **Nuclear**

Annual Energy Outlook 2007
U.S. Coal Consumption by Sector, 2005, 2010, 2020, and 2030 (quadrillion Btu)

- **2005**: 22.8
- **2010**: 24.2
- **2020**: 27.5
- **2030**: 35.0

**Sectors**:
- Electric Power
- Coal to Liquids
- Other

*Annual Energy Outlook 2007*
Agenda

• Extent and Sources of CO₂ Emissions

▷ Management & Capture

• Research Needs

Photo art: A. Benlow
Technology and Innovation Can Lead to Reductions in Carbon Emissions

Fuel Switching
Natural Gas
Renewables
Nuclear

Improve Efficiency
Demand Side
Supply Side

Sequester Carbon
Capture & Storage
Enhance Natural Sinks

Reduce Population
Reduce GDP

Photo art: A. Benlow
Reductions in Carbon Emissions
By Adoption of New Power Generation Technologies

<table>
<thead>
<tr>
<th>Generation Technology</th>
<th>Percent Reduction in CO₂ Emissions (Relative to Average PC Plant in 1999)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC (2000)</td>
<td>0</td>
</tr>
<tr>
<td>IGCC (2000)</td>
<td>25</td>
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<tr>
<td>PC (2010)</td>
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<tr>
<td>IGCC (2010)</td>
<td>75</td>
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<tr>
<td>NGCC (2000)</td>
<td>25</td>
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<tr>
<td>NGCC (2010)</td>
<td>50</td>
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<tr>
<td>All Technologies with Sequestration</td>
<td>100</td>
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</tbody>
</table>

Source: NETL, Scott Klara
Reductions in Carbon Emissions
By Switching to Natural Gas

Era of “Cheap” Gas May Be Over

• Supply cushion since mid-1980’s eroded
  – US supply flat past 5 years
  – Rapid decline curves for new wells
  – Canadian gas/LNG imports up from 4% in mid-1980s to 15%

• Spot Market Prices up 4-fold

• Projected 2-3% annual growth
  – up 60% thru 2020

• T&D infrastructure stressed
  – Need $120-150B investment to expand system

Source: USDOE
Reductions in Carbon Emissions
By Switching to Renewables

Wind, hydro, and geothermal - Not enough

Biomass - Transportation, land use, expense

Solar - Land use, capital cost, storage

Needed: An Affordable, Clean, and Abundant Energy Source
No Known Source Meets These Criteria

Source: USDOE
Technology and Innovation Can Lead to Reductions in Carbon Emissions

- Fuel Switching
- Improve Efficiency
- Sequester Carbon
- Reduce Population
- Reduce GDP
- Natural Gas
- Demand Side
- Capture & Storage
- Reduce Population
- Enhance Natural Sinks
- Renewables
- Supply Side
- Nuclear
- Enhance Natural Sinks

Photo art: A. Benlow
Reductions in Carbon Emissions
By Demand-side Efficiency

- Insulate your house
- Thermal windows
- High efficiency appliances
- Water-saving devices
- Natural lighting/solar mass

- Encourage industrial efficiency
- “Green” chemistry
- Recycle your waste

- Eat lower on the food chain
- Get close to your food

- Park your SUV
- Take the Bus
- Higher Price at the Pump
- Demand CAFÉ
- Buy the “Hybrid”
U.S. Sales of Unconventional Light-Duty Vehicles, 2015 and 2030 (thousand vehicles sold)

- Hybrids
- Flex Fuel
- Turbo Direct Injection Diesel
- Gaseous
- Electric
- Fuel Cell

Annual Energy Outlook 2007
Reductions in Carbon Emissions
By Greater Supply-side Efficiency

Electric Power
- Coal Production
- Power Delivery
- Power Generation

Petroleum
- Exploration & Production
- Refining & Delivery
- Transportation

Natural Gas
- Exploration & Production
- Pipelines & Storage
- Distributed Power Generation

Source: USDOE
Technology and Innovation Can Lead to Reductions in Carbon Emissions

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Utilization or Conversion???
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✍ Research Needs

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CAER Research on Carbon Management

Photo art: A. Benlow
CO₂ Capture from Electricity Generation

**Post-combustion capture**
- Fuel → Power & Heat → CO₂ separation → N₂, O₂, H₂O
- Flue gas → CO₂ separation

**Pre-combustion capture**
- Fuel → Gasification or partial oxidation shift + CO₂ separation → H₂ → Power & Heat → N₂, O₂, H₂O → CO₂
- Fuel → Air separation → N₂
- Air separation

**O₂/CO₂ recycle (oxyfuel) combustion capture**
- Fuel → Power & Heat → Recycle (CO₂, H₂O) → N₂
- Air separation
Research directed to Lowering Energy Penalty of CO₂ Capture Options

- **Post-Combustion Capture: PC + MEA (28-34%)**
  - Steam consumption for stripper: 20% of gross power output
  - Booster fan and agent pump for MEA scrubber: 3-4% of gross power output

- **Pre-combustion Capture: IGCC (total 15-24%)**
  - ASU + oxygen compression: 8-12% of gross power output
  - Selexol CO₂ separation: 2% of gross power output

- **In-situ Capture: Oxy-Fuel Combustion (total 22-32%)**
  - ASU: 15-20% of gross power output
  - Flue gas recirculation: 2% of gross power output
  - Possible CO₂ further enrichment (unknown)

** Compression Train: 5-10% of gross power output**
Possible Choices for CO2 Management

Oxy-Fuel Combustion
- Flue Gas Recirculating
  ~2% of gross power output
- Possible CO2 further enrichment
  Unknown, from 80-85% to 90% purity
- Possible Installation of LSD on Flue Gas Rirc.
  ~0.5% of gross power output

Possible Elimination of SCR
Gain 0.5% of gross power output

Oxygen Production Unit (ASU)
Cryogenic: 15-20% of gross power output

Oxygen Compression
Cryogenic: 8-12% of gross power output

Compression Train
5-10% of gross power output

Selexol CO2 Separation
~2% of gross power output

Possible Installation of Water/Moist Recovery from Exhaust Stream
Unknown

IGCC

Booster Fan and Agent Pump for MEA Scrubber
3-4% of gross power output

Steam Consumption for Stripper
~20% of gross power production

PC+MEA

[Additional text and numbers not clearly visible in the image]
Current Status of IGCC

• Mature technology for gasifier
• New wave pushed by GE, Shell and ConocoPhillips
• OEMs teamed with engineering companies to wrap
• RD&D
  – New catalyst/shift-reactor process to reduce $\text{H}_2\text{O}/\text{CO}$ ratio
  – Membrane separation
  – Sorbent development
  – Process integration
  – Oxygen production
Current Status of Oxy-Fuel

• Oxyfuel -- Commercial available for glass, steel and other sectors
  – Demo
    • Praxair & Foster Wheeler
      – Bahamas project
      – Fundación Ciudad de la Energía (CIUDEN)
    • B&W and Air Liquide
      – SaskPower (terminated?)
      – AEP
    • Alstom
      – Vattenfall
  – Ongoing RD&D for Utility
    • Vattenfall 30MWe plant
    • Air Liquide/B&W 4MMBtu and 40MMBtu plant
    • Alstom (3MWth FBC)
    • Universität Stuttgart (0.5MWth PC)
    • CANMET (0.3MWth PC and 1.0MWth FBC)
  – Air Separation Unit
    • Ion transport membrane (ITM) (Air Products, Praxair)
    • Ceramic autothermal recovery (CAR) (BOC Gases)
Post CO$_2$ Capture Process

- Absorption Processes (Liquid & Solid)
- Adsorption Process (Solid Surface, Ionic Liquid)
- Physical Separation (Membrane, Cryogenic Separation)
- Hybrid Solution (Mixed Physical - Chemical Solvent)
Post Combustion Scrubbing in Fossil Power Plants

**Challenges:**
- Low CO$_2$ partial pressure
  - 5-15 vol%  
- Low System Pressure
- 25-35% of plant output for auxiliary power.

**Capital Costs $500/kW**
- Three absorbers with same diameter as FGD, 50 ft packing.
- Strippers somewhat smaller.
Physical Absorption

- Physical solvent processes use organic or inorganic solvents to physically absorb acid gas components rather than react chemically.

- Removal of CO₂ by physical absorption processes based on the solubility of CO₂ within the solvents.

- The solubility of CO₂ depends on the partial pressure and on the temperature of the feed gas.

- Regeneration of the spent solvent can be achieved by flashing to lower pressure or by stripping with vapor or inert gas.
Chemical Absorption

• Chemical absorption processes are based on exothermic reaction of the solvent with the CO₂ in the feed gas stream.

• Chemical reaction must be reversible. The reactive solvent removes CO₂ in the absorber at low temperature. The reaction is then reversed by endothermic stripping process at high temperature and low pressure.

• Majority of chemical solvent processes use either an amine or carbonate solution.
Chemical Absorption Processes

- **Potassium Carbonate.**
  \[ \text{K}_2\text{CO}_3 + \text{CO}_2 + \text{H}_2\text{O} \Leftrightarrow 2\text{KHCO}_3 \]

- **Monoethanolamine (MEA)**
  \[ 2 \text{HO-CH}_2\text{-CH}_2\text{-NH}_2 + \text{CO}_2 \Leftrightarrow \text{HO-CH}_2\text{-CH}_2\text{-NH-COO}^- + \text{MEA}^+ \]

- **Ammonia**
  \[ 2\text{NH}_3 + \text{CO}_2 \Leftrightarrow \text{NH}_2\text{COO}^- + \text{NH}_4^+ \]
Chemical Absorption Scrubbing

- CO₂ lean Off Gas
- Absorber
- Raw Gas
- Rich Solution
- Lean/Rich Heat Exchanger
- Lean Solution
- Condenser
- CO₂ to Compression
- Regenerator
- Steam
- Reboiler

Diagram showing the process of chemical absorption scrubbing for CO₂ capture.
## Reagent Properties Affecting Makeup

<table>
<thead>
<tr>
<th></th>
<th>Cost $/lbmol</th>
<th>$P_{\text{amine, } 40^\circ C}$ atm x $10^3$</th>
<th>Degradation</th>
<th>Corrosion</th>
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</thead>
<tbody>
<tr>
<td>MEA</td>
<td>40</td>
<td>0.1</td>
<td>High</td>
<td>High</td>
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<tr>
<td>NH$_3$</td>
<td>5</td>
<td>200</td>
<td>None</td>
<td>High</td>
</tr>
<tr>
<td>PZ</td>
<td>300</td>
<td>0.1</td>
<td>Moderate</td>
<td>High</td>
</tr>
<tr>
<td>MDEA</td>
<td>300</td>
<td>0.003</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>K$_2$CO$_3$</td>
<td>40</td>
<td>0</td>
<td>None</td>
<td>High</td>
</tr>
</tbody>
</table>

Source: Rochelle, 2007
Current Status of Aqueous Scrubbing

• **Amine:** commercial-implementation on NG, food and chemical production
  – Kerr-McGee/ABB Lummus Crest Process
  – Fluor Daniel ECONAMINE FG Process
  – MHI’s KM-CDR process with KS solvent
  – Ongoing RD&D for utility flue gas
    • University of Texas at Austin
    • European Union integrated project “CO₂ from Capture to Storage” (CASTOR)
    • International Test Center (ITC) at University of Regina, Canada
    • MHI
    • UK CAER

• **Ammonia:** Commercial for fertilizer production
  – Ongoing RD&D for Utility’s flue gas
    • Alstom/EPRI 5MWth pilot plant at WE Energy - Pleasant Prairie Plant
    • Powerspan/NETL 1MWth slipstream at FirstEnergy’s Burger station
    • UK CAER/E-ON US 0.1MWth pilot plant
CAER CO₂ Capture Research

• Two Supported by E-ON US:
  • *Post-Combustion Process
    – Solvent-based CO₂ capture technologies
    – New concept development
      • Solid additives
      • Membrane for solution separation
  • *In-situ process (No external ASU)
    – Pressurized Chemical Looping Combustion Combined Cycle (PCLC-CC)

• Two for existing PC supported by GOEP
  – Feasibility Study on Using Algal Capture and Utilize CO₂ Source from Kentucky Power Plants
  – Development of Liquid Membrane for Solvent-Based Post-Combustion CO₂ Scrubber

• One for IGCC supported by CAER
  – Activated Carbons for CO₂ Capture from Coal-derived Pitch/Polymer Blends
Solvent-based CO$_2$ Capture Pilot-plant Objectives

- Provide a flexible pilot-scale platform to study a variety of CO$_2$ scrubbing processes for existing power stations.
- Study and optimize the power requirements for CO$_2$ scrubbing technologies.
- Solvent development and solvent management protocol (impact from coal impurities).
- Material Corrosion
0.1MWth Post-combustion CO$_2$ Capture Pilot Plant

- **Scrubber with height of 22-25 ft:**
  - 10” bottom tank, a 4” reaction zone, and a 8” reaction zone
  - Flexible configuration (open, tray-type or packed column)

- **Stripper with height of 15 ft**
  - 8” for reboiler section, 4” tower
  - 400°F and 450 psia (max)

- Range of gas flows: 10-50 scfm
- L/G range: 50 to 200
- Simulated flue gas
  - mixed from N$_2$, air, CO$_2$, HCl and SOx tanks.
- Will work on coal-derived flue gas
- generator
Research Progress

- Completed commissioning using K2CO3 Solvent
  - Easy solvent
  - Under utility flue gas cond., the CO2 removal efficiency at 3%-10%
- Pre-trail Study using K₂CO₃/Piperizane (PZ)
  - Solution preparation difficult (solved)
  - Low PZ solubility in lean solution (Precipitation of PZ at low Temp)
  - 100 hrs run using 1.5m K₂CO₃/PZ
- Baseline Testing using 30% MEA
  - Over two-month with 32 runs using ceramic packing
  - Foaming in stripper
  - MEA degradation vs. stripping temperature
  - Metal concentration profile
CO₂ capture vs. L/G Ratio

Graph showing CO₂ capture efficiency (%) vs. L/G ratio (0.001*gpm/cfm) for different gas flow rates (8 cfm, 10 cfm, 12 cfm, 15 cfm).
MEA Degradation vs. Time

![Graph showing MEA Degradation vs. Time](image)

- **Total Alkalinity for T200**
- **Linear (Total Alkalinity for)**

\[ y = -0.0044x + 5.4493 \]

\[ R^2 = 0.4141 \]
Carbon Management Research Group

- State-UK-Industry consortium
- Build on E-ON US investment in carbon management and emissions control
- Develop more energy and cost effective carbon management technologies
- Address specific materials, controls and waste management solutions
- Allow early adoption of technologies by Kentucky’s electric utilities
- $1 Million/yr match provided by State.
CO₂ Capture from Coal-to-Liquids

Coal 49,200 TPD → Coal Prep → Coal Gasification

Air → Air Separation → Sulfur Recovery


Sulfur → Sulfur Recovery

Power Generation → Power

Necessary hydrogen production / correction

Carbon Dioxide Compression → CO₂ to Storage 16,100 TPD

CO₂ 1790 TPD Stack

LPG NAPHTHA Diesel 120,000 BPD

CO₂ Compression CO₂ to Storage

CO₂ is captured from the process and compressed for storage.
Mitigating Carbon Impact from the Production of FT Fuels

• Enhanced modular reactor systems
• Improved catalysts for water-gas-shift
  – Reduce unwanted CO2 formation
• Use of biomass in FT processes
  – Biomass gasification
  – Gas cleaning
  – Utilization of biomass as hydrogen source
• Co-feed of Coal and Biomass for CTL