Fossil Energy and Carbon Capture: A Systems Perspective

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U.S. DOE/NETL
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Outline

• Overview of NETL
• Definitions, Overview of Power Production
• Motivation – CO₂, Costs, Water Use
• Post-combustion carbon capture technology
• Process Synthesis, Design & Optimization
  – Overview
  – Results
• Conclusions
National Energy Technology Laboratory

- Full-service DOE federal laboratory
- Dedicated to energy RD&D, domestic energy resources
- Fundamental science through technology demonstration
- Unique industry–academia–government collaborations
A Century of Energy Innovation

1910 - Coal research begins in Pittsburgh, PA

1918 - Petroleum research begins in Bartlesville, OK

1943 - Materials research begins in Albany, OR


1946 - Synthesis gas research begins in Morgantown, WV

1977 - All four sites join new U.S. Department of Energy

1996 - PA & WV sites form new Federal Energy Technology Center

1999 - FETC becomes National Energy Technology Laboratory (NETL)

2000 - National Petroleum Technology Office in OK joins NETL

2001 - NETL opens Arctic Energy Office in Fairbanks, AK

2005 - Albany Research Center joins NETL

2009 - OK office moves to Sugar Land, TX

Electricity Delivery & Energy Reliability

Energy Efficiency & Renewable Energy

Systems & Policy Analysis

Climate & Energy

Collaborative R&D Management

Alternative Fuels

Materials Science & Advanced Metallurgy

Enhanced Resource Recovery & Operational Safety
ORD Statistics

• **Employees:**
  – 205 Federal
  – 220 Contractor

• **University Collaboration:**
  – Regional University Alliance (CMU, Pitt, PSU, VT, WVU)
    • 91 Faculty Associates
    • 139 Graduate Students and Post-Docs
  – ORISE:
    • 63 Students and Post-Doctoral Students

• **Papers**
  – 140 papers in 2009
    • Up from 20 in 2000
    • Publications in high impact journals
  – 1900 citations to NETL papers

• **Recent Awards**
  – Nine R&D 100 Awards since 2007, including four in 2009
  – Five National FLC Excellence in Technology Transfer Awards; two in 2009
  – 70 Patent Applications in Process, 66 Total Issued Patents
  – 17 Active CRADAs
  – 11 Patent Licenses
Reducing the Carbon Footprint in Fossil Energy Production

• Increased Efficiencies
  – Advanced Steam Cycles
  – Advanced Gasification
  – Next Generation Combustion Turbines
  – Fuel Cells

• Fuel Flexibility
• Carbon Capture
  – >90% CO₂ capture
  – Minimize increase in COE
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Definitions – Single Cycle

• Pulverized Coal (PC) Plant
  – Burns coal to generate steam to run turbines (Rankine Cycle)
  – Classifications
    • Subcritical (~2500 psia, 36-40% efficient)
    • Supercritical (~3500+ psia, 40-45% efficient)
    • Ultrasupercritical (~4400 psia, 48% efficiency)
  – Post-combustion capture
    • Aqueous amine (MEA)

• Gas Turbine – single Brayton cycle
  – Inexpensive capital cost
  – Higher operating cost
  – Used for peaking power
Definitions – Combined Cycle

• IGCC - Integrated Gasification Combined Cycle
  – Gasifies coal (CO, H₂, CO₂)
    • Electricity from Combined Cycle
      – burning syngas in gas turbine (Brayton cycle)
      – steam generated from cooling syngas, turbine exhaust (Rankine cycle)
  – Pre-combustion capture
    • Shift reactor (syngas to hydrogen & CO₂)
    • Physical solvent to remove CO₂
      – Selexol, Rectisol

• NGCC – Natural Gas Combined Cycle
  – Lower capital cost
  – Lower inherent CO₂ emissions
  – Requires post-combustion carbon capture
Rankine Cycle

From http://en.wikipedia.org/wiki/Rankine_cycle
Brayton Cycle

From http://en.wikipedia.org/wiki/Brayton_cycle
Post-combustion capture (PC)

- ~70 mol% N₂
- ~13 mol% CO₂
- ~1.5 mol% CO₂
Oxycombustion (PC)
Pre-combustion capture (IGCC)
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U.S. CO₂ Emissions from Coal Plants

Previous study indicated that in 2030 80% of emissions will be from plants existing in 2010.

IGCC vs. PC with and without CCS

Net Plant Efficiency

<table>
<thead>
<tr>
<th></th>
<th>Avg IGCC</th>
<th>Avg IGCC CCS</th>
<th>PC-Sub</th>
<th>PC-Sub CCS</th>
<th>PC-Super</th>
<th>PC-Super CCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency, % (HHV Basis)</td>
<td>39.5</td>
<td>32.1</td>
<td>36.8</td>
<td>24.9</td>
<td>39.1</td>
<td>27.2</td>
</tr>
</tbody>
</table>

IGCC vs. PC with and without CCS

Cost of Electricity

LCOE by Cost Component

January 2007 Dollars, Coal cost $1.80/10^6 Btu, Gas cost $6.75/10^6 Btu
CCS = Carbon capture and storage
TS&M = transport, storage, and monitoring

Power Plant Water Withdrawal Requirements

*with and without CO₂ capture*

**Integrated Gasification Combined Cycle**

- GE: 6.8 gpm/MW net
- CoP: 9.5 gpm/MW net
- Shell: 9.2 gpm/MW net
- Subcritical: 9.9 gpm/MW net
- Supercritical: 11.1 gpm/MW net

**Pulverized Coal**

- 6.8 gpm/MW net
- 9.5 gpm/MW net
- 9.2 gpm/MW net
- 9.9 gpm/MW net

Source: Water Requirements for Existing and Emerging Thermoelectric Plant Technologies; NETL, August 2008
DOE/NETL Goals: CO$_2$ Capture

Minimum CO$_2$ Captured  Maximum Increase in COE
90%  30% for PC
     10% for IGCC

DOE/NETL Goals: Freshwater Minimization

• **Short-term goals (ready for commercial demonstration by 2015)**
  – Reduce freshwater withdrawal and consumption by > 50% for thermoelectric power plants equipped with wet recirculating cooling technology
  – Levelized cost savings > 25% compared to state-of-the-art dry cooling

• **Long-term goals (ready for commercial demonstration by 2020)**
  – Reduce freshwater withdrawal and consumption by > 70% for thermoelectric power plants equipped with wet recirculating cooling technology
  – Levelized cost savings > 50% compared to state-of-the-art dry cooling
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Subcritical PC Plant

Legend:
- Cooling Water
- CO₂ Absorbent
- Flue Gas
- Recovered CO₂
- Recovered Steam
- Steam Cycle

Diagram showing the flow of materials and processes in a subcritical PC plant, including water, lime, air, and coal, with components such as a mixer, filter, desulfurization, boiler, and turbines.
Aqueous Amine Scrubbing
Solid Sorbents

Moving Bed
Steady-state
1 Dimensional PDE model

Fluidized Bed
Steady-state, three phase model (bubble, wake and emulsion) with interphase mass transfer
Oxy-fuel Combustion

- Oxygen + flue gas recycle = easy CO₂ capture.
- Innovative oxygen production technologies and integration with whole process needed.
- Validated simulation tools:
  - Enabling rapid & multiple retrofit and greenfield.
  - Requires establishing simulation appropriate to new combustion environment.

Chalmer’s Furnace (Khare et. al, 2008)
Chemical Looping

\[ \text{N}_2 + \text{O}_2 \text{ (vitiated air)} \]

- CO + H₂O
- CO₂ + H₂O

Parametric Study of geometry and flow rate
- Maximize Coal Utilization
- Minimize Char/Ash entering air reactor

Upper Fluid Bed Zone
- char & MeO mix and circulate
- \( U(\text{gas}) > U_{mf}(\text{MeO}) > U_{mf}(\text{char}) \)

Lower Moving Bed Zone
- char & MeO separate
- \( U_{mf} \text{(MeO)} > U(\text{gas}) > U_{mf} \text{(char)} \)

\[ \text{Carbon + metal oxide} = \text{CO}_2 + \text{metal} \]

\[ \text{Metal + air (oxygen)} = \text{metal oxide} \]
Compression

- 5 casing (10 stage) compression
- Intercoolers 265°F to variable T
- Water returned to process
- Final pressure 2200 psia
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Challenges

- Large-scale problem
  - 2 billion tons CO₂ from coal by 2020 in US
  - Flue gas: 5 million lb/hr for 550MW PC plant

- No existing economical solution
- No framework for developing & evaluating optimized designs
- Difficulty re-using existing models/simulations
- Inconsistent assumptions & evaluation methods

- Approach
  - Process synthesis, design & optimization
    - Process integration
    - Nonlinear interactions across units/subsystems
    - Simulation-based optimization
  - Multi-criteria decision-making tools
    - Include water resource considerations
Simulation INTERface (SINTER)

- Set simulation variables
- Supports structural changes
  - Feed stage
  - Number of stages
  - (not supported internally)
- Retrieves results
- Perform post-processing
  - Cost estimation
  - Objective function calculations
Modular Framework for Process Design and Optimization

Power Plant Module

CO₂ Capture Module

Compression Module
Capital Cost vs. NUHR
NUHR vs. Water Use
<table>
<thead>
<tr>
<th></th>
<th>Best Net Unit Heat Rate</th>
<th>Best Capital Cost</th>
<th>Best Water Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUHR (Btu/kWh)</td>
<td>14,145</td>
<td>14,392</td>
<td>14,157</td>
</tr>
<tr>
<td>Capital Cost ($/kW&lt;sub&gt;net&lt;/sub&gt;)</td>
<td>1,186</td>
<td>988</td>
<td>1,188</td>
</tr>
<tr>
<td>Overall Net Power Output (MW)</td>
<td>354.7</td>
<td>348.6</td>
<td>354.4</td>
</tr>
<tr>
<td>Total Capital Cost (Capture &amp; Compression only)</td>
<td>$421 MM</td>
<td>$345 MM</td>
<td>$421 MM</td>
</tr>
<tr>
<td>Solvent Flow rate (gpm)</td>
<td>7,070</td>
<td>7,470</td>
<td>6,970</td>
</tr>
<tr>
<td>Lean Solvent Loading (mol CO&lt;sub&gt;2&lt;/sub&gt;/mol amine)</td>
<td>0.214</td>
<td>0.218</td>
<td>0.212</td>
</tr>
<tr>
<td>Rich Solvent Loading (mol CO&lt;sub&gt;2&lt;/sub&gt;/mol amine)</td>
<td>0.454</td>
<td>0.444</td>
<td>0.454</td>
</tr>
<tr>
<td>No. Absorber Stages</td>
<td>20</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>No. Stripper Stages</td>
<td>14</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Cooling Water Evaporation (lb/MWh&lt;sub&gt;net&lt;/sub&gt;)</td>
<td>5,280</td>
<td>5,507</td>
<td>5,247</td>
</tr>
</tbody>
</table>
Conclusions

• Demonstrated importance of optimizing systems
  – Large potential improvement over initial design
• Essential for comparing potential CC technology
  – Many non-intuitive interactions
  – Understand competing objectives
• Significant optimization/integration opportunities remain
  – Solid sorbents
  – Advanced solvents
  – Oxycombustion
  – IGCC
  – Compression
Tasks Required for Deployment

Pilot Scale Demonstration Projects Commercial Deployment

Decision Making

Particle/Device Scale

Process Synthesis & Design

Process Operations

Basic Data

Uncertainty Quantification - Optimization - Integration
A new ionic liquid that exhibits high CO₂ permeability and CO₂/H₂ selectivity was identified with this method.

Identify promising concepts and designs ➔ Develop optimal designs ➔ Quantify technical risk in scale up

Accelerate learning during development & deployment
Acknowledgements: Research Team

• Optimization and computational infrastructure
  – ModeFrontier integration & multi-criteria, simulation-based optimization - NETL (Miller/Eslick)
  – Derivative-free surrogate model development – CMU (Sahinidis/Cozad/Chang)
  – Simultaneous Superstructure-based Optimization – CMU (Grossmann/Yang)
  – Synthesis of Integrated IGCC Systems – CMU (Grossmann/Biegler/Kamath)

• Module development
  – Base plant modules
    • Predictive Plant Models (PC/IGCC) – NETL (Miller/Eslick)
    • Development of Predictive Turbine Models – NETL (Liese)
    • Oxycombustion Plant Model – NETL Albany (Summers/Oryshchyn/Harendra)
  – Carbon capture modules
    • Equilibrium & rate-based amine capture – NETL (Miller/Eslick)
    • Solid sorbent capture systems – NETL (Miller/Lee)
    • Membrane-based separation systems – NETL (Miller/Morinelly)
    • Compression system – NETL (Miller/Eslick)
    • Synthesis of Optimal PSA Cycles for CO2 Capture from Flue Gas – CMU (Biegler/Agarwal)
    • Synthesis of Optimal PSA Cycles for Hydrogen/CO2 Separation – CMU (Biegler/Vetukuri)
    • Cryogenic separation and hydrate-based separation – NETL (van Osdol)
  – Water-specific activities
    • Treated Municipal Wastewater for Power Plant Cooling – CMU (Dzombak/Hsieh)
    • Modeling Nontraditional Sources of Power Plant Water
      – IIT (Abbasion/Arastoopour/Walker/Safari/Strumendo)
    • Water from Oxycombustion – NETL Albany (Summers/Oryshchyn/Harendra)