The Outlook for Advanced Post-Combustion CCS Processes

Edward S. Rubin
Department of Engineering and Public Policy
Department of Mechanical Engineering
Carnegie Mellon University
Pittsburgh, Pennsylvania

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Background

- Our research group at Carnegie Mellon has been looking at and modeling a variety of current and advanced technologies for carbon capture and storage (CCS) as a greenhouse gas mitigation option for power plants using fossil fuels or biomass, including:
  - Pre-combustion
  - Post-combustion, and
  - Oxy-combustion processes for CO₂ capture

Advanced Capture Technology Models Under Development*

- Post-Combustion Capture
  - Advanced membranes
  - Calcium looping
  - Solid sorbents
    - Amine-based
    - Activated carbon-based
    - Metal organic frameworks
  - Ionic liquids
- Oxy-Combustion Capture
  - Oxygen production
  - Carbon processing unit
  - Gas recycle options
- Pre-Combustion Capture
  - Chemical looping
  - Ionic liquids
  - Sorbent-enhanced WGS

Objective of This Talk

- Focus on post-combustion CO₂ capture
- Summarize preliminary findings on the potential of advanced technologies to significantly reduce the cost of CO₂ capture relative to current amine-based systems

*In projects supported by DOE/NETL and Stanford GCEP
The IECM Framework

IECM: A Tool for Analyzing Power Plant Design Options

- 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

IECM Software Package

Fuel Properties
- Heating Value
- Composition
- Delivered Cost

Plant Design
- Conversion Process
- Emission Controls
- Solid Waste Mgmt
- Chemical Inputs

Cost Factors
- O&M Costs
- Capital Costs
- Financial Factors

Power Plant Models

Graphical User Interface

Plant and Fuel Databases

Plant & Process Performance
- Efficiency
- Resource use

Environmental Emissions
- Air, water, land

Plant & Process Costs
- Capital
- O&M
- COE

Technologies Currently in IECM
(Version 8.0.2)

*Additional capture options under development include solid sorbent and calcium looping systems for post-combustion (PC or NGCC plants), a chemical looping system for IGCC, and an advanced oxy-combustion system.

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The CMU Project Team

- Kyle Borgert
- Justin Glier
- Karen Kietzke
- John Kitchin
- Hari Mantripragada
- Ed Rubin
- Wenqin You
- Haibo Zhai

Current Post-Combustion Capture Technology

CO₂ Capture Using an Amine-Based System

Flue Gas (from FGD) → Absorber → Cooler → Regenerator

- Absorber: CO₂ capture
- Regenerator: CO₂ release

CO₂ Capture Systems on Power Plants

- Bellingham gas-fired plant
- Warrior Run coal-fired plant
- Plant Barry coal-fired plant

Flue Gas (to atmosphere) → Flue Gas (to compression) → CO₂ product (via compression)
First Large-Scale Demonstration Project Now Operating

- Sask Power Boundary Dam (Canada): 110 MW coal-fired unit;
- 90% capture +EOR (~ 1 Mt CO2/yr ); Startup September 2014

Cost of Post-Combustion CCS for New Power Plants Using Current Technology

<table>
<thead>
<tr>
<th>Incremental Cost of CCS relative to same plant type</th>
<th>Supercritical Pulverized Coal Plant</th>
<th>Natural Gas Combined Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Increases in power generation cost ($/kWh)*</td>
<td>~ 60–80%</td>
<td>~ 30–45%</td>
</tr>
</tbody>
</table>

*Added cost to consumers will be much smaller, reflecting the CCS capacity in the generation mix at any given time. Retrofit of existing plants typically has a higher cost.

Advanced CO₂ Capture Technologies

Examples of Advanced Technologies: Everything beyond Present
Characteristics of Advanced Carbon Capture Systems

- The technology is not yet deployed or available for purchase at a commercial scale
  - Current stage of development may range from concept to large pilot or demonstration project
- Process design details still preliminary or incomplete
- Process performance not yet validated at scale, or under a broad range of conditions
- May require new components and/or materials that are not yet manufactured or used at a commercial scale

IECM Technologies for Post-Combustion CO₂ Capture

- **Liquid solvent systems**
  - Amines (MEA, FG+)
  - Chilled ammonia
  - Ionic liquids*
- **Solid sorbent systems**
  - Amine-based*
  - Activated carbons*
  - Metal organic frameworks*
  - Calcium looping*
- **Membrane systems**
  - Once-through systems
  - Sweep gas (recycle) systems*

Preliminary Findings for Overall Plant Performance

For designs achieving 90% CO₂ capture:

- Many of the advanced processes for post-combustion capture have energy penalties comparable to current amine systems, based on the current state of technology
- The two systems with better performance than amines were an advanced membrane design (2-stage, 2-step with air sweep) and a calcium looping system
  - Caveat: Effects of flue gas impurities on process and system performance remains to be determined

Preliminary Conclusion:
Better capture materials and process designs are needed to get major performance improvements
Typical Cost Trend of a New Technology

How can we do a better job of estimating the cost of advanced technologies?

Seven Simple Steps to Improve Cost Estimates for New Technologies

1. Use non-cost metrics for earliest-stage technologies
2. Define the proper system boundary for cost estimates
3. Use standard costing methods
4. Quantify cost elements appropriately for FOAK plant
5. Use learning curves when estimating NOAK costs
6. Characterize and quantify uncertainties
7. Report cost metrics that are useful and unambiguous

A Standardized Costing Method is Now Available

Recent guidelines from International Task Force

Items to be included in a power plant or capture technology cost estimate
**DOE/EPRI Guidelines for Process and Project Contingency Cost**

<table>
<thead>
<tr>
<th>Current Technology Status</th>
<th>Process Contingency (% of process capital)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New concept with limited data</td>
<td>40+</td>
</tr>
<tr>
<td>Concept with bench-scale data</td>
<td>30-40</td>
</tr>
<tr>
<td>Small pilot plant data</td>
<td>20-35</td>
</tr>
<tr>
<td>Full-sized modules operated</td>
<td>5-20</td>
</tr>
<tr>
<td>Process is used commercially</td>
<td>0-10</td>
</tr>
</tbody>
</table>

- **Factor applied** ... to quantify the uncertainty in the technical performance and cost of the commercial-scale equipment* based on the current state of technology. - EPRI TAG

- **Factor covering the cost of additional equipment or other costs that would result from a more detailed design of a definitive project at an actual site.** - EPRI TAG

Most studies of advanced capture systems assume much smaller process contingencies (e.g., 0 to <20%).

<table>
<thead>
<tr>
<th>EPRI Cost Classification</th>
<th>Design</th>
<th>Process Contingency (%TPC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(~AACE Class 5/4) Class I</td>
<td>Simplified</td>
<td>30-50</td>
</tr>
<tr>
<td>(~AACE Class 3) Class II</td>
<td>Preliminary</td>
<td>15-30</td>
</tr>
<tr>
<td>(~AACE Class 3) Class III</td>
<td>Detailed</td>
<td>10-20</td>
</tr>
<tr>
<td>(~AACE Class 1) Class IV</td>
<td>Finalized</td>
<td>5-10</td>
</tr>
</tbody>
</table>

*Most Class I-III studies assume ≤10% Contingency Costs Assumptions for Advanced Capture Technology

**Table: Contingency Costs Assumptions for Advanced Capture Technology**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical Assumption</th>
<th>EPRI/DOE Guidelines*</th>
<th>Capital Cost Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Contingency (%TPC)</td>
<td>10%</td>
<td>~40%</td>
<td>~30%</td>
</tr>
<tr>
<td>Project Contingency (%TPC)</td>
<td>10%</td>
<td>~30%</td>
<td>~20%</td>
</tr>
<tr>
<td>TOTAL Contingency (%TPC)</td>
<td>20%</td>
<td>~70%</td>
<td>~50%</td>
</tr>
</tbody>
</table>

*Based on current state of technologies for membrane, solid sorbents, and other post-combustion processes with limited data.

The total contingency cost for advanced capture processes is significantly under-estimated in most cost studies, leading to systematically low capital cost estimates.

**Insights on Technology Innovation**

- Research on technology innovation shows that in addition to sustained R&D, “learning by doing” is needed to achieve commercial cost reductions. Thus, …

- To realize $N^{th}$-of-a-kind costs you have to build $N$ plants

**Conclusion: High capital costs will hinder the entry of new technologies**

**Another Challenge for New Technology: Baseline technology does not stand still**

Amine-based capture systems have been steadily improving

**Conclusion:** Advanced post-combustion capture technologies face stiff headwinds on the path to commercialization

E.S. Rubin, Carnegie Mellon
Acknowledgements

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Thank You

rubin@cmu.edu