Pilot Test of Novel Electrochemical Membrane System for Carbon Dioxide Capture and Power Generation
Hossein Ghezel-Ayagh
2016 NETL CO2 Capture Technology Meeting
August 8-12, 2016
Pittsburgh, PA
Electrochemical Membrane (ECM) Technology Development Path

DE-FE0007634
Electrochemical Membrane for Carbon Dioxide Capture and Power Generation

- Preliminary Technical and Economic Feasibility Study (PT&EFS)
- Technology Gap Identification including Effects of Trace Contaminants
- Environmental, Health & Safety (EH&S) Review
- Bench-Scale Testing of 0.2 T/D ECM (>90% Carbon Capture)
**Electrochemical Membrane (ECM) Technology Development Path**

**DE-FE0026580**

Pilot Test of Novel Electrochemical Membrane System for Carbon Dioxide Capture and Power Generation
- Techno-Economic Analysis (TEA) Updates Achieving 30% less COE of Baseline Supercritical PC Plant with Amin Carbon Capture
- EH&S Updates
- Design a Small Pilot Scale Plant (>40 T/D) Prototypical of a Commercial Unit
- Fabricate and Install the Pilot Scale Plant
- Conduct >2 months Tests at a Coal Plant Facility Demonstrating >90% Capture (>95% CO2 Purity)

**DE-FE0007634**

Electrochemical Membrane for Carbon Dioxide Capture and Power Generation
- Preliminary Technical and Economic Feasibility Study (PT&EFS)
- Technology Gap Identification including Effects of Trace Contaminants
- Environmental, Health & Safety (EH&S) Review
- Bench-Scale Testing of 0.2 T/D ECM (>90% Carbon Capture)
ECM Project Team Structure

The FCE team is comprised of diverse organizations with expertise in key functional areas:

FuelCell Energy Inc. (FCE), Danbury, CT

- **Key experience**: Manufacturing and commercialization of fuel cell power plant systems in sizes ranging from 300 kW to Multi-MW.
- **Project Role**: Prime Contractor

AECOM, Austin, TX
Process Technologies Organization

- **Key Experience**: Global leader in providing engineering, construction and technical services including pollution control systems
- **Project Role**: Support TEA (review ECM system design, equipment and plant costing), pilot system key equipment specification and selection, flue gas clean-up system design
### Project Schedule and Budget

#### Budget Period 1 (10/1/2015 - 12/31/2016)
- **Government Share**: $4,033,959
- **Cost Share**: $1,008,490

#### Budget Period 2 (1/1/2017 - 12/31/2017)
- **Government Share**: $7,765,275
- **Cost Share**: $5,466,983

#### Budget Period 3 (1/1/2018 - 3/31/2019)
- **Government Share**: $3,200,766
- **Cost Share**: $2,253,433

#### Total Project (10/1/2015 - 3/31/2019)
- **Government Share**: $15,000,000
- **Cost Share**: $8,728,906

### Techno-Economic Analysis (TEA) & EHS
- Initial
- Update

### Pilot Plant BOP Design
- BOP Equipment

### Pilot Plant Fabrication
- ECM Module
- Integration and Factory Acceptance Tests

### Pilot Plant Operation
- Install
- Commission
- Test & Evaluation
- De-Commission or Continue Tests

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#### Government Share Costs

<table>
<thead>
<tr>
<th></th>
<th>BP 1</th>
<th>BP 2</th>
<th>BP 3</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2015</strong></td>
<td>Q3 Q4</td>
<td>Q1 Q2</td>
<td>Q3 Q4</td>
<td>Q1 Q2</td>
</tr>
<tr>
<td><strong>2016</strong></td>
<td>Q3 Q4</td>
<td>Q1 Q2</td>
<td></td>
<td></td>
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<tr>
<td><strong>2017</strong></td>
<td>Q3 Q4</td>
<td></td>
<td></td>
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<tr>
<td><strong>2018</strong></td>
<td></td>
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<td><strong>2019</strong></td>
<td></td>
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</tbody>
</table>

#### Cost Share

- **Budget Period 1**: 80.00%
- **Budget Period 2**: 58.68%
- **Budget Period 3**: 41.32%
- **Total Project**: 63.21%
Electrochemical Membrane (ECM) Technology Overview
**ECM Operating Principle**

The driving force for CO$_2$ separation is electrochemical potential, not pressure differential across the membrane.

**Net Results**
- Simultaneous Power Production and CO$_2$ Separation from Flue Gas of an Existing Facility
- Excess Process Water Byproduct
- Complete Selectivity towards CO$_2$ as Compared to N$_2$
Modular Technology

ECM Assembly

ECM Stack (Using 400 ECM Assemblies)

ECM Module (4 Stacks)

Enclosed Module

Modules Utilized in Large-Scale Applications
Techno-Economic Analysis
Application of ECM for CO₂ Capture from a 550MW PC Plant

Combined Electric Power and Carbon-dioxide Separation (CEPACS) System Concept Implementation for 550 MW Reference Supercritical PC Plant*

CEPACS system produces:
- Supercritical CO₂ (90% CO₂ capture from PC Plant)
- Excess Process Water
- Additional 319 MW of clean AC power @ 40.7% Efficiency (based on HHV NG)

* Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 2a, DOE/NETL-2010/1397, September 2013.
• CEPACS System increases power output of Baseline PC plant by 58%
• PC plant retrofitted with CEPACS system is 43% (12.3 percentage points) more efficient than amine scrubbing for carbon capture
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• PC plant retrofit with CEPACS system is 43% (12.3 percentage points) more efficient than amine scrubbing for carbon capture

• PC + CEPACS System CO₂ Emissions are 55% lower than PC w/ Amine due to power generation (vs. consumption) @ 90% capture level
• PC plant retrofitted with CEPACS system has lower emissions of NO\textsubscript{x}, SO\textsubscript{x}, and Particulate Matter (PM) than a PC plant retrofitted with Amine scrubber for CO\textsubscript{2} capture, below MATS limits

• CEPACS system produces excess process water, resulting in:
  – 58% less raw water withdrawal than with amine scrubbing
  – 20% less raw water withdrawal compared to baseline plant without CO\textsubscript{2} capture
• PC plant retrofitted with CEPACS system has 31% lower COE than amine scrubbing
- PC plant retrofitted with CEPACS system has 31% lower COE than amine scrubbing

- ECM-Based CEPACS System can meet DOE Target of <$40/tonne CO₂ captured (2011 USD)
ECM Testing Results
(DE-FE0007634)

- ECM Tolerance to Flue Gas Contaminants
- Bench-scale (11.7m²) ECM System
## ECM Flue Gas Contaminants Tolerance: Summary

<table>
<thead>
<tr>
<th>Flue Gas Contaminant</th>
<th>Highest Concentration Tested by PNNL, with Negligible Power Degradation</th>
<th>Concentration in Cathode Inlet Gas after Polishing FGD, Estimated by AECOM</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₂</td>
<td>1 ppmv</td>
<td>0.18 ppmv</td>
<td>Performance losses due to short-term SO₂ exposure up to 40ppm were fully reversible</td>
</tr>
<tr>
<td>Se</td>
<td>10 ppbv</td>
<td>0.30 ppbv</td>
<td>No apparent degradation over 860 hours.</td>
</tr>
<tr>
<td>Hg</td>
<td>250 ppbv</td>
<td>0.08 ppbv</td>
<td>Expected form is predominantly elemental Hg. No apparent degradation over 1100 hours.</td>
</tr>
<tr>
<td>HCl</td>
<td>200 ppbv</td>
<td>12.7 ppbv</td>
<td>No apparent degradation over 900 hours.</td>
</tr>
</tbody>
</table>

- Tests of ECM with simulated trace contaminants in the flue gas were performed at Pacific Northwest Laboratory (PNNL)
- Based on trace contaminants tests and AECOM performance estimates, a polishing wet-FGD scrubber was designed to sufficiently clean flue gas for ECM operation
• ECM Provides a Co-benefit for NO$_x$ Destruction
• Test results have shown > 70% at High Inlet NO$_x$ Concentration (200 ppm) During Carbon Capture under System Conditions
Bench-Scale Demonstration Test Results

Completed testing of CEPACS demonstration system using simulated PC flue gas:

- >100 ton/year CO$_2$ capture capability
- >10 kW peak power production
- 15,715 hours total runtime
Net CO₂ captured >120 Tonnes and net DC electric power generated >110 MWh
ECM cell performance data for NGCC and PC plant flue gases at 93% carbon capture:

- ECM is capable of operating on flue gases with a wide range of CO₂ partial pressure
- System features (e.g. supplemental air addition, product recycle) allow tuning of cathode-side composition to optimize ECM performance
Pilot Plant Design
### MW-Class Pilot CEPACS System Performance Summary

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value(s)</th>
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<tbody>
<tr>
<td><strong>ECM Gross Power</strong></td>
<td></td>
</tr>
<tr>
<td><strong>DC Power</strong></td>
<td>2015.7 kW</td>
</tr>
<tr>
<td><strong>Energy &amp; Water Input</strong></td>
<td></td>
</tr>
<tr>
<td>Natural Gas Fuel Flow</td>
<td>216.8 scfm</td>
</tr>
<tr>
<td>Fuel Energy (LHV)</td>
<td>3759.3 kW</td>
</tr>
<tr>
<td>Water Consumption @ Full Power</td>
<td>0 gpm</td>
</tr>
<tr>
<td><strong>Consumed Power</strong></td>
<td></td>
</tr>
<tr>
<td>AC Power Consumption</td>
<td>(450.3) kW</td>
</tr>
<tr>
<td>Inverter Loss</td>
<td>(100.8) kW</td>
</tr>
<tr>
<td><strong>Total Parasitic Power Consumption</strong></td>
<td>(551.1) kW</td>
</tr>
<tr>
<td><strong>Net Generation &amp; Efficiency</strong></td>
<td></td>
</tr>
<tr>
<td>CEPACS Plant Net AC Output</td>
<td>1464.6 kW</td>
</tr>
<tr>
<td><strong>Electrical Efficiency (LHV)</strong></td>
<td>39.0 %</td>
</tr>
<tr>
<td><strong>Carbon Capture</strong></td>
<td></td>
</tr>
<tr>
<td>Total Carbon Capture %</td>
<td>92 %</td>
</tr>
<tr>
<td>CO₂ Captured, Tons per Day</td>
<td>64 T/D</td>
</tr>
<tr>
<td>CO₂ Purity</td>
<td>99.6 %</td>
</tr>
</tbody>
</table>
**Electrical Balance of Plant (EBOP) Skids**
*Converts direct current produced by ECM to alternating current*
- EBOP includes dc-to-ac invertors, transformers, and programmable logic controllers (PLCs)
- Shipped directly to installation site

**Mechanical Balance of Plant (MBOP) Skids**
*Preheats flue gas, conditions & humidifies fuel prior to delivering to module, purifies CO₂*
- Designed by FCE
- Major mechanical equipment sourced globally and assembled in MBOP skids
- Shipped directly to installation site

**Vendor-Supplied Equipment Skids**
*CO₂ Compressors, Chiller, Flue Gas Polishing*
- Specified by FCE / AECOM
- FCE / AECOM QC oversight
- Shipped directly to installation site
Pilot Demonstration Site Selection Process

• Initial screening of several coal based power generating sites were conducted
• Two sites were investigated for detailed analysis
• Site selection criteria includes implementation cost and accessibility of the necessary infrastructure for pilot plant tests

• James M. Barry Electric Generating Station, Alabama Power/Southern Co.
  • Location: Bucks, AL
  • Nameplate Capacity: 1,771 MWe, Mix of Coal and Natural gas

• Abbott Power Plant, University of Illinois
  • Location: Champaign, Ill
  • Nameplate Capacity: 84 MWe, Mix of coal and natural gas
Captures and Concentrates Exhaust from:
- Coal power plant
- Natural gas power plant
- Industrial process

Proven Technology:
- Leverages commercial fuel cell technology
- Project underway to demonstrate MW-class pilot plant for capture from coal flue gas

Economical:
- Produces additional power vs power reduction
- Generates return on capital vs operating expense

Additional Benefits:
- 70% reduction in NOx
- Clean water production

JDA with ExxonMobil
- Collaboration partner with extensive resources
  - World’s largest energy company & public gas producer
  - Leading expert & experience with sequestration
- Opportunity
  - Integration with combined cycle gas plants
  - Global market opportunity measured in Gigawatts

Hwaseong, South Korea
59 MW Fuel Cell System
Acknowledgements

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