Initial Engineering Design of a Post-Combustion CO₂ Capture System for Duke Energy’s East Bend Station Using Membrane-Based Technology

DE-FE0031589

Dr. Des Dillon
EPRI, Sr. Technical Leader

Dr. Sai Gollakota
NETL, Federal Project Manager

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Project Overview

- **Funding**
  - Federal Share: $1,625,244
  - Non-Federal Share: $406,485
  - TOTAL $2,031,729

- **Project Performance Dates**
  - 04/06/2018 to 03/31/2020

- **Project Participants**
  - **Prime:**
    - Electric Power Research Institute
  - **Sub-contractors:**
    - Membrane Technology and Research
      - Trimeric
    - Nexant Inc.
      - Bechtel
  - **Site Host:**
    - Duke Energy

- **Project Objective**
  - Perform an initial engineering design and cost estimate for a commercial-scale, membrane-based, post-combustion CO$_2$ capture system retrofit to Duke Energy’s 600MWe coal-fired East Bend Unit.
Background - MTR Polaris Membrane

- MTR has developed a CO$_2$ selective polymeric membrane material and module - the MTR Polaris membrane
- This provides higher CO$_2$ permeance for post combustion flue gas applications than existing polymeric membranes

Images Courtesy of MTR
Background – Membrane Module

- Membranes are widely used for desalination and natural gas sweetening
- The largest existing systems are similar in scale to those required for a 550MWe coal fired power plant

Images Courtesy of MTR
Background - Low Pressure Drop Modules

- Compact modular system design using high permeance membranes
  - Reduces CAPEX and
  - Overall system pressure drop

Images Courtesy of MTR
MTRs CO₂ Capture Development to Date

Feasibility study (DE-NT43085)
- Sweep concept proposed
- Polaris membrane conceived

APS Red Hawk NGCC Demo
- First Polaris flue gas test
- 250 lb/d CO₂ used for algae farm

APS Cholla Demo (DE-FE5312)
- First Polaris coal flue gas test
- 1 TPD CO₂ captured (50 kWₑ)

NCCC 1 MW, Demo (DE-FE5795)
- 11,000 hours of 1 TPD system operation
- 1 MW, (20 TPD) system operation

Low Pressure Mega Module (DE-FE7553)
- Design and build a 500 m² optimized module

Hybrid Capture (DE-FE13118)
- Membrane-solvent hybrids with UT, Austin

B&W Integrated Test

Images Courtesy of MTR
Advantages of the Membrane Capture Process

- Simple, passive operation with no chemical handling, emissions, or disposal issues
- Membrane not effected by O\(_2\), SO\(_x\) or NO\(_x\); co-capture possible
  - O\(_2\), SO\(_x\) or NO\(_x\) permeate and therefore impact the overall process design
- Modular technology – high volume manufacturing to lower cost, pre-assembled, containerized skids
- No steam use → no modifications to existing boiler/turbines
- Near instantaneous response; high turndown possible
- Very efficient at partial capture (40-60% CO\(_2\) recovery)
Challenges of the Membrane Capture Process

- Develop a design that will **minimize the impact** on the power plant by disrupting as little of the existing facilities as possible.
  - Also shorten the amount of downtime before the plant can resume normal operations

- Develop a design that will **minimize the cost** of each tonne of captured CO₂ while also maintaining the net 600 MW output of the East Bend Station (EBS).
  - This will be done by optimizing the percentage of CO₂ captured (~60%) and by adding a natural-gas-fired combustion turbine (CT) or possibly a combined cycle to offset the new auxiliary loads
Initial Conceptual Flow Diagram
Partial CO$_2$ Capture with 2 Stage Membrane Process

Preliminary Design Case for the East Bend Unit
- 2 membrane arrangement
- Aiming for ~60% CO$_2$ Capture from the coal plant
- No boiler recycle
Technical Approach 1/2

- Following a data gathering task that will include several site visits to the EBS, a preliminary process design will be developed for one Post Combustion Capture (PCC) system which captures CO₂ from the entire flue gas stream of the power plant.

- This preliminary design will then be subjected to a series of analyses to examine various options for minimizing the cost of CO₂ capture on a $/tonne-captured basis.

- The analysis will also examine several options for providing the PCC system’s auxiliary power via a CT-based power plant.

- Once an optimized process design has been identified, that design will be detailed and documented in a complete Process Design Package (PDP).
Technical Approach 2/2

- As part of this effort a HAZOP and constructability review of the design will be conducted.
- The PDP data will be used to carry out a techno-economic analysis that will include a +/-30% accuracy capital cost estimate as well as an estimate of the first year cost of electricity and $/tonne cost of CO\textsubscript{2} capture for the retrofitted power plant.
- The marginal operating cost of the retrofitted plant with also be calculated and used in a unit dispatch model to predict how the retrofit will impact how often the coal plant is called on to operate.
## Project Schedule

<table>
<thead>
<tr>
<th>Task Name</th>
<th>Dates</th>
<th>Budget Period 1</th>
<th>Budget Period 2</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Start</td>
<td>End</td>
<td>M1/M2</td>
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<tr>
<td>1.1 Project and Risk Management (EPRI)</td>
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<td>1.2 Financial and Project Reporting (EPRI)</td>
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<td>1.3 Technology Maturation Plan (MTR)</td>
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<tr>
<td>TASK 2: Develop Design Basis document (Nexant Lead)</td>
<td>4/1/2018</td>
<td>9/30/2018</td>
<td>M3</td>
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<tr>
<td>TASK 3: Establish Base Case Model (Nexant Lead)</td>
<td>7/1/2018</td>
<td>9/30/2018</td>
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<td>TASK 4: System analysis of Integration options (EPRI Lead)</td>
<td>8/1/2018</td>
<td>04/31/2013</td>
<td>M5</td>
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<td>4.1 Optimize CO2 Capture Plant Design (MTR)</td>
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<td>4.2 Evaluate Options for Aux. Power (EPRI, Nexant)</td>
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<td>4.3 Finalize Design Configuration (EPRI, MTR, Nexant)</td>
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<td>DECISION POINT: Examine and Review Retrofit Options</td>
<td>1/31/2019</td>
<td>4/15/2019</td>
<td>M6</td>
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<td>TASK 5: Finalize Overall Retrofit PC Design (EPRI Lead)</td>
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<td>9/30/2019</td>
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<td>5.1 Design Package of the Membrane CCS System (MTR)</td>
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<td>5.2 Design Package for BOP &amp; Aux. Power (EPRI &amp; Nexant)</td>
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<td>M9</td>
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<td>5.3 Preliminary HAZOP Review (Nexant, Bechtel, MTR &amp; Duke)</td>
<td>10/30/2019</td>
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<td>M10</td>
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<td>5.4 Constructability Review (Nexant, Bechtel &amp; Duke)</td>
<td>10/30/2019</td>
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<td>TASK 6: Techno-Economic Analysis (EPRI Lead)</td>
<td>8/1/2018</td>
<td>12/31/2019</td>
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<tr>
<td>6.1 Capital Cost Estimation of Integrated PCC Design (Nexant)</td>
<td>10/30/2019</td>
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<td>M10</td>
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<tr>
<td>6.2 O&amp;M Cost Estimation of Integrated PCC Design (Nexant, EPRI)</td>
<td>10/30/2019</td>
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<td>6.2 TEA and Dispatch Analysis (EPRI &amp; Duke)</td>
<td>12/31/2019</td>
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<td>TASK 7: Final Report Preparation (EPRI Lead)</td>
<td>1/1/2020</td>
<td>3/31/2020</td>
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Key Accomplishments

1. Host site agreed to EPRI team’s proposed capture system’s auxiliary power source
2. Identified all electrical loads and initiated refinement of the power demands for the full-scale CO₂ membrane capture system
3. Completed membrane arrangement and CO₂ processing unit flow diagram and developed preliminary equipment list
4. Completed a comprehensive review of process cooling requirements and verified that the preliminary layout of the overall retrofit plant will fit the space available
Key Accomplishment 1
Host site agreed to EPRI team’s proposed capture system’s auxiliary power source

- The retrofit team prepared and presented to site hosts Duke Energy an assessment of 4 auxiliary power options for the membrane capture system.
- A single Gas Turbine Simple Cycle Power island was recommended as best suited for the East Bend station application.
- Duke Energy accepted the project team’s recommendation. This represents a significant decision point in the project plan.
Supplying the Membrane System Power Requirements

- Unlike solvent PCC systems - No steam requirement, but power is required to drive the membrane systems fans, blowers, vacuum compressors pumps and CO₂ compression

- 4 ways to supply power have been considered:
  - Option 1: New natural gas-fired simple cycle,
  - Option 2: New natural gas-fired combined cycle
  - Option 3: New simple cycle with HRSG steam to the coal plant FWH
  - Option 4: Auxiliary power supplied from the existing coal station

- Examine which option is best suited for MTR PCC integration implementation at EBS
Aux Power Option 1: New natural gas-fired simple cycle
Aux Power Option 1: New natural gas-fired simple cycle
Aux Power Option 1: New natural gas-fired simple cycle
Aux Power impact on cost of CO₂ Capture & COE

$3.50/MSCF NG cost

Note: Preliminary evaluation to help facilitate auxiliary power selection (NOT FINAL RESULTS)
Results From Auxiliary Power Assessment

- Similar cost of CO₂ capture for all integration options (within margin of error)
- Selection of best option may be based on overall ease of integration instead of cost
- Recommend simple cycle (Option 1) using single GE7F04 turbine
  - Lowest upfront cost of all the external power options considered
  - Allow phased implementation of feedwater preheat (Option 3)
  - Enough temperature & heat available for future EBS HP feedwater preheating if desired
  - Potential for future addition of a full size HRSG, should the owner at a later date, consider additional power export of value
  - GE 7F.04 was the old GE 7FA GT and its operation is well established commercially
Key Accomplishment 2

Identified all electrical loads and initiated refinement of the power demands for the full-scale CO$_2$ membrane capture system

- After selecting the power island, the retrofit team continued to optimize and refine the power load of the capture process to ensure they stay within the capabilities of the power island while maximizing CO$_2$ captured.
- The largest loads are blowers, membrane permeate compressors, refrigerant compressors and CO$_2$ pumps.
- In addition, the specific impacts of the East Bend site ambient conditions, flue gas water content, and air in-leakage from the power plant on the final capture system design have been examined.
## Summary of Aux Power and Cooling Water Requirements by Subsystem

<table>
<thead>
<tr>
<th>Item</th>
<th>Normal Motor Power, MW</th>
<th>Cooling Water, gpm</th>
<th>Cooling Duty, MMBtu/hr</th>
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<tbody>
<tr>
<td>Flue Gas Blower</td>
<td>18.6</td>
<td></td>
<td></td>
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<tr>
<td>DCC w/ DFGD</td>
<td>3.3</td>
<td>31,946</td>
<td>319.6</td>
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<tr>
<td>MTR – Total Power Consumption</td>
<td>130.0</td>
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<tr>
<td>MTR – CW Load for Power Input</td>
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<td>39,914</td>
<td>399.3</td>
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<tr>
<td>MTR – H$_2$O Condensing CW Load</td>
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<td>32,996</td>
<td>330.1</td>
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<td>MTR – Misc. Utilities</td>
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<tr>
<td>Dedicated CT System for PCC</td>
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<tr>
<td>Dedicated CW System for PCC</td>
<td>5.6</td>
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<tr>
<td>BOP</td>
<td>1.3</td>
<td></td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>160.3</strong></td>
<td><strong>104,856</strong></td>
<td><strong>1,049.0</strong></td>
</tr>
</tbody>
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*Note: Preliminary Numbers to Help facilitate the Aux Power selection (NOT FINAL RESULTS)*
Direct Contact Cooler

- 2 trains to handle 100% of EBS flue gas (FG) from WFGD
- Each train consists of a FG blower; a DCC contactor with circulation pumps and plate-and-frame heat exchangers; and the associated FG ducting
- Each contactor has two packed bed sections
  - Deep Flue Gas Desulfurization (DFGD) bottom bed to reduce the FG sulfur content down below 5 ppm with caustic scrubbing to meet CO₂ purity specifications (per QGES)
  - Direct Contact Cooler (DCC) top bed to cool the FG, minimizing its moisture content before feeding the MTR membranes
Key Accomplishment 3
Completed membrane arrangement and CO₂ processing unit flow diagram definition and preliminary equipment list

- MTR and Trimeric prepared detailed CO₂ and refrigeration process flow diagrams (PFD).
- Expanding on the original concept outline PFD, this detailed diagram shows the entire process including heat integration between flue gas, cold CO₂ process streams, and refrigerant streams as well as individual equipment items selected to facilitate capture.
- The PFD is being used to engage with vendors for specific equipment items, performance and cost.
PFD Development: Flue Gas Conditioning

Image Courtesy of Trimeric
PFD Development: CO2 Purification Unit

Image Courtesy of Trimeric Corporation

CO2 Recycle

Main Compression

Refrigerate

Dry

Vacuum

Cool

Refrigerate

Liquid CO2

Heat

Expand

Heat

Expand

Heat

CO2 Recycle

Heat

Pump

> 95% CO2

Image Courtesy of Trimeric
PFD Development: Refrigeration System

Image Courtesy of Trimeric
Key Accomplishment 4
Completed a comprehensive review of process cooling requirements and verified that the preliminary layout of the overall retrofit plant will fit the space available

- The membrane capture system preliminary cooling water duty and the cooling water flow rate requirements have been defined as well as the design of the direct contact cooler.
- These allow the capture island’s additional cooling towers to be sized and positioned.
- An initial layout of the cooling towers and the capture system (including its tie-ins to the existing station flue gas) has been drafted.
- This illustrates that the membrane retrofit can fit within the space available on the existing East Bend site.
East Bend Station Plot Plan

Stack

Wet FGDs

Ohio River
East Bend Station w/ MTR PCC Plant Plot Plan

Stack

Wet FGDs

CO₂ Capture island

New Power Island

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Note: Preliminary Layout (NOT FINAL RESULTS)
MTRs CO₂ Capture Development - Current Projects

Self-Assembly Isoporous Supports, CA (DE-FE31596)
- Improve gas transport through support layer
- Enables a reduction in membrane area
- Build and test new membrane at NCCC

Pilot Testing at TCM, Norway (DE-FE31587)
- 1 MWe - advanced Polaris™ membrane
- Partial capture for low cost-of-capture
- New modular construction

Pilot Testing at TCM, Norway (DE-FE31603)
- 1 MWe - Hybrid testing with TDA
- Membrane + solid sorbent for 90% capture
- Selective CO₂ recycle using sorbents

Full-Scale Pre-FEED at Duke Energy’s East Bend Station, KY (DE-FE31589)
- 460 MWe – using Advanced Polaris™
- Partial capture and modular membrane
- Rapid retrofit deployment

Large-Pilot Testing at WY ITC, WY (DE-FE31587)
- Phase I – Design ~16 MWe pilot; secure host site
- Phase II – FEED and permitting
- Phase III – Fabricate, install and operate

Images Courtesy of MTR
Acknowledgement and Disclaimer

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