Slipstream pilot plant demonstration of an amine-based post-combustion capture technology for CO$_2$ capture from coal-fired power plant flue gas

DOE funding award DE-FE0007453

2013 NETL CO$_2$ Capture Technology Meeting
Krish R. Krishnamurthy, Linde LLC
July 8-11, 2013
Pittsburgh, PA
The Linde Group Overview and Carbon Capture Expertise

Linde pursues technology development and solution offer in all three CC pathways

Post-combustion capture
- Linde expertise
  - Scrubbing system
  - CO₂ processing (drying, compression and purification)
  - CO₂ suitable for storage

Pre-combustion capture
- Linde expertise
  - Air separation unit
  - Shift
  - CO₂ recovery
  - CO₂ to storage

Oxyfuel combustion
- Linde expertise
  - Air separation unit
  - CO₂ condensation
  - CO₂ liquefaction
  - CO₂ to storage

Leveraging Synergies

- Founded: 1879
- Sales (2012): $20 billion (€15.3b)
- Employees: 61,965
- Countries: >100
- US Linde Gas HQ: Murray Hill, NJ
- US Linde Engineering Facilities: Blue Bell, PA; Tulsa, OK & Holly Springs, GA
### Project Budget: DOE funding and cost share

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<tbody>
<tr>
<td>DOE Funding</td>
<td>$2,670,773</td>
<td>$9,367,628</td>
<td>$2,754,564</td>
<td>$14,792,365</td>
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<td>Cost Share</td>
<td>$667,943</td>
<td>$2,341,907</td>
<td>$688,641</td>
<td>$3,698,091</td>
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<tr>
<td>Total Project</td>
<td>$3,337,716</td>
<td>$11,709,535</td>
<td>$3,443,205</td>
<td>$18,490,456</td>
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**Cost share commitments:**

- Linde: $3,107,352
- BASF: $493,360
- EPRI: $97,379

Project spend until end of Budget Period 1: $3,240,192
### Project Participants

<table>
<thead>
<tr>
<th>Partner/Organization</th>
<th>Lead contact(s)</th>
<th>Key Role(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOE-NETL</td>
<td>Andrew P. Jones, Project Manager</td>
<td>-Funding &amp; Sponsorship</td>
</tr>
<tr>
<td>Linde LLC</td>
<td>Krish Krishnamurthy, PI Stevan Jovanovic, Technical Lead</td>
<td>-Prime contract -Overall program management -Operations and testing</td>
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<tr>
<td>BASF</td>
<td>Sean Rigby (BASF Corp)</td>
<td>-OASE® blue technology owner -Basic design -Solvent supply and analysis</td>
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<tr>
<td>EPRI</td>
<td>Richard Rhudy</td>
<td>-Techno-economics review -Independent validation of test analysis and results</td>
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<tr>
<td>Southern Co./NCCC</td>
<td>Frank Morton Michael England</td>
<td>-NCCC Host site (Wilsonville, AL) -Infrastructure and utilities for pilot plant build and operations</td>
</tr>
<tr>
<td>Linde Engineering, Dresden</td>
<td>Torsten Stoffregen Harald Kober</td>
<td>-Basic engineering -Support for commissioning -Operations and testing</td>
</tr>
<tr>
<td>SFPC (Linde Engineering North America)</td>
<td>Lazar Kogan Keith Christian</td>
<td>-Detailed engineering -Procurement and installation</td>
</tr>
</tbody>
</table>
Overall Objective

— Demonstrate Linde-BASF post combustion capture technology by incorporating BASF’s amine-based solvent process in a 1 MWel slipstream pilot plant and achieving at least 90% capture from a coal-derived flue gas while demonstrating significant progress toward achievement of DOE target of less than 35% increase in levelized cost of electricity (LCOE)

Specific Objectives

— Complete a techno-economic assessment of a 550 MWel power plant incorporating the Linde-BASF post-combustion CO₂ capture technology to illustrate the benefits
— Design, build and operate the 1MWel pilot plant at a coal-fired power plant host site providing the flue gas as a slipstream
— Implement parametric tests to demonstrate the achievement of target performance using data analysis
— Implement long duration tests to demonstrate solvent stability and obtain critical data for scale-up and commercial application
Project Overview: Key Drivers

— Post-combustion CO₂ capture technology is flexible and can be applied to both new and existing power plants

— Solvent based technologies are today the leading option as they have been commercially applied at large scale in other applications (e.g. natural gas processing, syngas purification)

— Advanced amine based technologies with properly selected solvent can overcome performance and stability issues with the current state-of-the-art reference MEA solvent

— The specific advanced amine based solvent (BASF OASE® blue) offers key performance benefits (increased CO₂ loading, reduced regeneration steam requirements, stable in the presence of oxygen and significant potential for lower capital costs)
BASF OASE® blue Technology Development
Designed for PCC Applications

Equilibrium Kinetics Stability

Fundamental Lab Scale R&D: Advanced Solvents Screening, Development, Optimization

BASF Miniplant, Ludwigshafen, Germany: Solvent Performance Verification

0.45 MWe PCC Pilot, Niederaussem, Germany: Preliminary Process Optimization
Niederaussem Pilot Plant: Main results of Phase I

- **OASE blue** has a 20% lower specific energy consumption
- **OASE blue** has a significant lower solvent circulation rate
- Even after six months of operation, the oxidation rate of OASE blue was extremely low.
Niederaussem Pilot Phase II: Long term testing evaluating materials, solvent degradation and emissions reduction

Status: Phase II (10/2012)
- > 20 000 hours operation
- > 4 800 t CO₂ captured
- availability: 97%
Linde-BASF advanced PCC plant design*  

Advanced emission control system

High capacity structured packing

Optimized Blower Concept

Gravity Flow Interstage Cooler

Treated flue gas to stack

Flue gas blower

Make-up water

Water Cooler

Absorber

Interstage Cooler

Solvent Filter

Solvent Cooler

Water Wash

Desorber

Rich/Learn Solvent Hex

Reboiler

Condensate

LP_Pipe Steam

Condensate return

Optimized Energy Consumption


*Patent Applications 2010-2012
Comparative PCC Performance Results
Linde-BASF vs Reference DOE-NETL Case*

*Reference Case # 10 of DOE-NETL 2007/1281 Report
Power plant efficiency improvements and LCOE reductions with Linde-BASF PCC technology

Incremental improvements in power plant efficiency from MEA based PCC to LINDE-BASF LB-2 Option

Net HHV Efficiency
- NETL - MEA: 24.9%
- Advanced Solvent: 1.76%
- PCC Optimization (LB-1): 1.39%
- Heat and Power Integration (LB-2): 29.4%


Incremental Reductions in Levelized Cost Of Electricity from MEA based PCC to LINDE-BASF LB-2 Option

LCOE (2007$/MWh)
- NETL - MEA: $119.6
- Advanced Solvent: $114.1
- Process Enhancements: $109.0
- PCC Optimization (LB-1): $103.5
- Heat and Power Integration (LB-2): $101.2
- LINDE-BASF: $101.2

Linde-BASF PCC Plant Design for 550 MWe PC Power Plant

- Single train PCC design for ~13,000 TPD CO₂ capture
- 40-50% reduced plot area to 180m x 120 m
Linde-BASF experience in large scale carbon capture

CO₂ capture in natural gas processing: Re-injection Project - Hammerfest

World’s first industrial project to deliver CO₂ separated onshore from the well-stream back offshore for re-injection into a reservoir

— Partnership with StatoilHydro Petroleum
— Melkoya island near the town of Hammerfest, Norway
— CO₂ sequestration and re-injection integral part of the Hammerfest LNG project. Linde performed design, EPC and commissioning
— One dedicated well for CO₂ storage in a sandstone formation sealed by shale cap.
— Re-injection started in April 2008
— BASF’s OASE® purple process used in CO₂ capture

700,000 tpa CO₂ capture and re-injection (part of world scale LNG project, Snøhvit, Norway)
# Project Schedule and Milestones: Budget Period 1

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
<th>Details</th>
<th>Start</th>
<th>End</th>
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<tbody>
<tr>
<td>1</td>
<td>1. Project management and planning</td>
<td>A. Submit project management plan</td>
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<td>2</td>
<td>2. Conduct kick-off meeting</td>
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<td>3</td>
<td>3. Host site agreement executed</td>
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<td>4. Techno-economic evaluation on a 550 MWe power plant</td>
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<td>5. 2.1 Basic scope for power plant with CO2 capture and compression</td>
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<td>6</td>
<td>6. 2.2 Detailed design of the power plant</td>
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<td>7. 2.3 Economic analysis of the power plant with CO2 capture and compression</td>
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<td>8</td>
<td>8. 2.4 Complete initial techno-economics analysis on a 550 MWe power plant</td>
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<td>9</td>
<td>9. 3. Pilot plant design optimization &amp; basic design</td>
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<td>10</td>
<td>10. 3.1 Solvent selection and basic process design</td>
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<td>11. 3.2 Parametric design optimization and confirmation of design basis</td>
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<td>12. 3.3 Basic design package of the pilot plant</td>
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<td>13. 4. Complete basic design and engineering of the 1 MWe pilot plant to be tested at the NCCC</td>
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<td>14. 5. Pilot plant system design and engineering</td>
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<td>15. 5.1 Preliminary engineering studies</td>
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<td>16</td>
<td>16. 5.2 Process design review and HazOP</td>
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<td>17. 5.3 Detailed design and engineering</td>
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<td>18. 5.4 Development of equipment packages</td>
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<td>19. 5.5 Site design, engineering and foundations specification</td>
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<td>20. 6. Pilot plant cost and safety analysis</td>
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<td>21. 6.1 Preliminary pilot plant EHS assessment</td>
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<td>22. 6.2 Transportation and lifting study</td>
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<td>23. 6.3 Cost optimization and updated pilot plant cost build up</td>
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<td>24. 6.4 Complete pilot plant engineering and cost analysis for the 1 MWe unit to be tested at NCCC</td>
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<td>25</td>
<td>25. G - Go decision to build pilot plant</td>
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**Budget Period 1 tasks successfully completed on time and on schedule**
Project Schedule and Milestones: Budget Period 2

Budget Period 2 tasks initiated in March 2013 and are currently in progress
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</table>
|  - Design review  
|  - PSR 1 and 2  
|  - Hazop  
|  - 60% model review  
|  - Equipment packages  
|  - 3-D model  
|  - 30% model review  
|  - Update P&ID (Hazop actions)  
|  - Module package  
|  - RFQ to vendors  

PSR: Process Safety review; P&ID: Process and Instrumentation Diagrams; RFQ: Request for quotes; Hazop: Hazard and operability study
Task 3: Design Selection
Pilot Plant Layout

Optimized plant layout investigated
3D Model of NCCC site with Linde-BASF Pilot Plant
3D Model of Linde-BASF 1 MWe Pilot Plant

Absorber

Stripper

Structural support for windload protection
3D Model of Linde-BASF Pilot Plant modular design (3 level structure)
### Project progress: Key Project Milestones (Budget Period 1)

#### Status


- Submit project management plan (03/09/2012) ✓
- Conduct kick-off meeting with DOE-NETL (11/15/2011) ✓
- Complete initial techno-economic analysis on a 550 MWel power plant (05/04/2012) ✓
- Complete basic design and engineering of a 1 MWe pilot plant to be tested at NCCC (06/20/2012) ✓
- Execute host site agreement - completed 01/09/2013 ✓
- Complete initial EH&S assessment - Completed 12/14/2012 ✓
- Complete detailed pilot plant engineering and cost analysis for the 1 MWe pilot plant to be tested at NCCC – Completed by 02/15/2013 ✓

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Project continuation request to proceed to Budget Period 2 was presented to DOE-NETL on Jan 14, 2013 and was accepted.
Key design and engineering features and decisions

- Joint design basis development (Linde/BASF and SCS/NCCC) for the nominal 1 MWe pilot plant
- Leveraged Niederaussem pilot plant experience for early design selection decision on target solvent, pilot plant preliminary sizing, process control and analytical sampling and measurement
- Pilot plant maximum testing capability to 30 TPD CO2 or 1.5 MWe equivalent – confirmed utility availability with some upside margins
- Integrated modeling approach for detailed engineering – start with the existing NCCC facility model with tie-in points defined and integrated into pilot plant model to avoid conflicts in build phase
- Equipment and module packages sent to multiple vendors and vendor selection performed based on cost, capability and eagerness for involvement in project
- Concrete column sections evaluated but determined to impact project timeline significantly – currently allowing for future swapping the SS bottom section of absorber with concrete section.
- Current pilot plant equipment procurement and build schedule (BP2) requires BP2 timeframe extension by 3-months. No cost time extension agreed with DOE-NETL.
<table>
<thead>
<tr>
<th>Decision Point</th>
<th>Basis for Decision/Success Criteria</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Completion of Budget Period 1</td>
<td>Successful completion of all work proposed in Budget Period 1</td>
<td>Completed</td>
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<tr>
<td></td>
<td>Demonstrate a 10% reduction in capital costs with Linde-BASF CO2 capture process</td>
<td>30.5 to 34.7% for PCC and 16.6 to 17.3% for integrated power plant</td>
</tr>
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<td>Demonstrate a LCOE increase of less than 65% over the baseline</td>
<td>62.2% and 58.8% for 2 options considered</td>
</tr>
<tr>
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<td>Submission of an Executed Host Site Agreement</td>
<td>Completed</td>
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<tr>
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<td>Submission of a Topical Report – Initial Techno-Economic Analysis</td>
<td>Completed</td>
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<tr>
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<td>Submission of a Topical Report – Initial EH&amp;S Assessment</td>
<td>Submitted</td>
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<tr>
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<td>Submission of a Topical Report – Detailed Pilot Plant Engineering and Cost Analysis</td>
<td>Submitted</td>
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<tr>
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<td>Submission and approval of a Continuation Application in accordance with the terms and conditions of the award</td>
<td>Submitted &amp; approved by DOE-NETL</td>
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</table>
### Progress on procurement of pilot plant equipment, modules and site installation contract (Linde Engineering – North America, formerly SFPC)

<table>
<thead>
<tr>
<th>Item</th>
<th>Progress/Accomplishments to date</th>
<th>Key activity planned for completion</th>
</tr>
</thead>
</table>
| Heat Exchangers                                | - Production & testing/inspection completed  
- Shipped to module fabricator                                                               | - Installation on modules                                                                          |
| Pumps                                          | - Production & perf. testing completed  
- Performance testing & acceptance                                                              | - Installation on modules                                                                          |
| Columns and pressure vessels                   | - Absorber & stripper final drawing complete and approved for production  
- Other pressure vessels produced                                                               | - Produce, inspect and ship to site (Jan 2014)  
- Ship vessels to module fab.                                                                    |
| Column internals                               | - Order placed. Final drawings complete & approved for production                               | - Produce & ship for assembly in column                                                            |
| Modules                                        | - Order finalized with design updates  
- Structural steel assembly in progress                                                          | - Finish module assembly  
- Ship to site (Dec 2013)                                                                        |
| Site installation contract                     | - Contractor finalized and terms agreed                                                           | - Construction team mobilization at site (Oct. 2013)                                              |
| Instruments, control valves, analyzers and other| - Order placed for all items  
- Several items shipped to module fab.                                                           | - Install on modules  
- Selected items direct to site                                                                   |
 Specification and Purchase of Process Equipment for the Pilot Plant

Plate frame Heat Exchangers

**Heat Exchangers**
- Order placed for all HX
- Produced by vendor
- Tested & inspected at vendor site
- Shipped to module fabricator

Process Pumps

**Process and Cooling Water Pumps**
- Order placed for all pumps
- Produced by vendor
- Tested & inspected at vendor site
- Shipped to module fabricator
Accomplishments to date (Module):
1. Detailed specifications and 3-D models of the module packages completed.
2. Purchase orders completed and vendor packages received and reviewed.
3. Modules are currently in fabrication.

Planned work by module fabricator:
1. Complete structural assembly.
2. Install equipment and piping, instruments, electrical etc.
3. Test fit and inspection.
Accomplishments to date (SCS at NCCC site):
1. Civil design engineering completed.
3. FRP flue gas header designed & installed.
4. Sump pump, flue gas blower, pre-scrubber packing and internals purchased.

Planned work by SCS (July 2013 to Feb 2014):
1. Install epoxy coating on slab and sump pumps.
2. Install blower and pre-scrubber internals and test performance.
3. Install solvent system modifications.
4. Install new impeller for demin water pump.
Key Project Milestones (Budget Periods 2 and 3)


- Complete purchase orders and fabrication contracts for the 1 MWe pilot plant (06/30/2013)
- Complete shop fabrication of equipment and modules and associated engineering checks (12/15/2013)
- Complete site preparation and foundation installations at NCCC to receive pilot plant (11/15/2013)
- Complete installation of the 1 MWe pilot plant at NCCC (02/28/2014)
- Mechanical completion of 1 MWe pilot plant at NCCC (05/28/2014)

**Budget Period 3 (Jun. 1, 2014 – Feb. 28, 2016)**

- Complete pilot plant start up and demonstrate plant operation at steady state (08/31/2014)
- Develop pilot-scale parametric test plan (09/30/2014)
- Complete 1 MWe pilot-scale parametric tests (02/28/2015)
- Develop pilot-scale long duration test plan (03/31/2015)
- Complete 1 MWe pilot-scale long duration tests (11/30/2015)
- Complete updated techno-economic analysis (01/31/2016)
- Complete updated EH&S assessment (02/28/2016)
Acknowledgement and Disclaimer

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Thank you for your attention!

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Krish R. Krishnamurthy, Linde LLC
July 8-11, 2013
Pittsburgh, PA