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

2012 NETL CO$_2$ Capture Technology Meeting
Krish R. Krishnamurthy, Linde LLC
July 9-12, 2012
Pittsburgh, PA
The Linde Group Overview and Carbon Capture Expertise

- **Founded**: 1879
- **Sales (2011)**: $18 billion
- **Employees**: 50,000
- **Countries**: >100
- **US Linde Gas HQ**: Murray Hill, NJ
- **US Linde Engineering Facilities**: Blue Bell, PA; Tulsa, OK & Holly Springs, GA

Leveraging Synergies

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
  - Air
  - Feedstock
  - Combustion and steam generation
  - Steam
  - Power generation and heat recovery

**Pre-combustion capture**
- **Linde expertise**
  - Air separation unit
  - Shift
  - CO₂ recovery
  - CO₂ in storage
  - Oxygen
  - Raw syngas
  - Conditioned syngas
  - Gasification
  - Power generation and heat recovery

**Oxyfuel combustion**
- **Linde expertise**
  - Air separation unit
  - Recycled CO₂
  - CO₂ in storage
  - Oxygen
  - Recycled CO₂
  - CO₂ liquefaction
  - CO₂ in storage
  - Combustion and steam generation
  - Steam
  - Power generation and heat recovery

Linde Engineering
- Technology-focused

- Air Separation
  - Global #1
  - Global #2
  - Global #3
- Hydrogen/Syn Gas
  - Global #1
  - Global #2
- Olefins
  - Global #2
  - Global #3
- Natural Gas
  - Global #3

Linde Gas - Tonnage
- World-class operations

- HyCO Tonnage Plants
  - >70 plants
- ASU Tonnage Plants
  - >300 plants
- ECOVAR Std Plants
  - >1,000 plants

Leveraging

Synergies
<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>
</tbody>
</table>
| Linde LLC                    | Krish Krishnamurthy, PI Stevan Jovanovic, Technical Lead | -Prime contract  
-Overall program management  
-Operations and testing |
| BASF                         | Iven Clausen (BASF SE) Sean Rigby (BASF Corp)       | -OASE® blue technology owner  
-Basic design  
-Solvent supply and analysis |
| EPRI                         | Richard Rhudy                                       | -Techno-economics review  
-Independent validation of test analysis and results |
| Southern Co./NCCC            | Frank Morton Michael England                        | -N CCC Host site (Wilsonville, AL)  
-Infrastructure and utilities for pilot plant build and operations |
| Linde Engineering, Dresden   | Torsten Stoffregen Harald Kober                     | -Basic engineering  
-Support for commissioning  
-Operations and testing |
| SFPC (Linde Eng)             | Lazar Kogan                                         | -Detailed engineering  
-Procurement and installation |
**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 schedule and milestones: Budget Period 1

<table>
<thead>
<tr>
<th>ID</th>
<th>Task Name</th>
<th>Qtr 4, 2011</th>
<th>Qtr 1, 2012</th>
<th>Qtr 2, 2012</th>
<th>Qtr 3, 2012</th>
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<th>Qtr 1, 2013</th>
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<td>1. Project management and planning</td>
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<tr>
<td>2</td>
<td>a. Submit project management plan</td>
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<td>3</td>
<td>b. Conduct kick-off meeting</td>
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<td>4</td>
<td>c. Host site agreement executed</td>
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<td>5</td>
<td>2 Technoeconomic evaluation on a 550 MWe power plant</td>
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<td>6</td>
<td>2.1 Design and scope for power plant with CO2 capture and compression</td>
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<tr>
<td>7</td>
<td>2.2 Detailed design of the power plant</td>
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<td>2.3 Economic analysis of the power plant with CO2 capture and compression</td>
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<td>9</td>
<td>d. Complete initial techno-economics analysis on a 550 MWe power plant</td>
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<tr>
<td>10</td>
<td>3 Pilot plant design optimization &amp; basic design</td>
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<tr>
<td>11</td>
<td>3.1 Solvent selection and basic design &amp; process design</td>
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<td>3.2 Parametric design optimization and confirmation of design basis</td>
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<td>3.3 Basic design package of the pilot plant</td>
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<td>14</td>
<td>d. Complete basic design and engineering of the 1 MWe pilot plant to be tested at the NCCC</td>
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<td>4. Pilot plant system design and engineering</td>
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<td>4.2 Process design review and HazIDP</td>
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<td>18</td>
<td>4.3 Detailed design and engineering</td>
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<td>19</td>
<td>4.4 Development of equipment packages</td>
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<td>4.5 Site design, engineering and foundations specification</td>
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<td>21</td>
<td>5. Pilot plant cost and safety analysis</td>
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<td>22</td>
<td>5.1 Preliminary pilot plant E&amp;S cost analysis</td>
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<td>23</td>
<td>5.2 Transportation and lifting study</td>
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<td>24</td>
<td>g. 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>Go - No Go decision to build pilot plant</td>
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</table>

**Budget Period 2: March 2013 to February 2014 (Pilot plant procurement, fabrication and installation)**

**Budget Period 3: March 2014 to November 2015 (Pilot plant operations, parametric and long-duration testing)**
## Project Budget: DOE funding and cost share

<table>
<thead>
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<td>DOE Funding</td>
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<td>$9,822,449</td>
<td>$2,754,564</td>
<td>$14,792,365</td>
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<td>Cost Share</td>
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<td>$2,455,612</td>
<td>$688,641</td>
<td>$3,698,091</td>
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<td>Total Project</td>
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<td>$12,278,061</td>
<td>$3,443,205</td>
<td>$18,490,456</td>
</tr>
</tbody>
</table>

Cost share commitments:
- Linde: $3,107,352
- BASF: $493,360
- EPRI: $97,379
Key Project Milestones (Budget Period 1)


- 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 (10/31/2012)
- Complete initial EH&S assessment (10/31/2012)
- Complete detailed pilot plant engineering and cost analysis for the 1 MWe pilot plant to be tested at NCCC (01/31/2013)
Key Project Milestones (Budget Periods 2 and 3)


— Complete purchase orders and fabrication contracts for the 1 MWe pilot plant (03/29/2013)
— Complete shop fabrication of equipment and modules and associated engineering checks (07/31/2013)
— Complete site preparation and foundation installations at NCCC to receive pilot plant (08/15/2013)
— Complete installation of the 1 MWe pilot plant at NCCC (11/30/2013)
— Mechanical completion of 1 MWe pilot plant at NCCC (02/28/2014)

Budget Period 3 (Mar. 1, 2014 – Nov. 30, 2015)

— Complete pilot plant start up and demonstrate plant operation at steady state (05/31/2014)
— Develop pilot-scale parametric test plan (06/30/2014)
— Complete 1 MWe pilot-scale parametric tests (11/30/2014)
— Develop pilot-scale long duration test plan (12/31/2014)
— Complete 1 MWe pilot-scale long duration tests (08/31/2015)
— Complete updated techno-economic analysis (10/31/2015)
— Complete updated EH&S assessment (11/30/2015)
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)
## Post combustion CO₂ capture: Challenges compared to CO₂ removal in NG/LNG plants

<table>
<thead>
<tr>
<th></th>
<th>NG/LNG</th>
<th>Flue gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>50 – 100 bars</td>
<td>1 bara</td>
</tr>
<tr>
<td>CO₂ partial pressure</td>
<td>1 – 40 bars</td>
<td>30 – 150 mbars</td>
</tr>
<tr>
<td>Flowrate</td>
<td>up to 60 mio scf/hr</td>
<td>up to 120 mio scf/hr</td>
</tr>
<tr>
<td>Gas composition</td>
<td>CH₄, C₂H₆, ..., CO₂, H₂S, COS, CₓHᵧ,S, H₂O</td>
<td>N₂, O₂, H₂O, CO₂, (SOₓ) NOₓ</td>
</tr>
<tr>
<td>Treated gas specification</td>
<td>50 ppm – 2 % CO₂</td>
<td>CO₂ removal rate (90 %)</td>
</tr>
<tr>
<td></td>
<td>S &lt; 4 – 10 ppm</td>
<td>low amine emissions</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>not a key issue</td>
<td>of highest priority</td>
</tr>
</tbody>
</table>

- large volume flows @ low pressure
- solvent stability
- emissions of solvent
- overall power plant efficiency losses
BASF OASE® blue Technology Development
Designed for PCC Applications

**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 key results

- >90% carbon capture rate achieved
- >20% improvement in specific energy compared to MEA
- New BASF solvent is very stable compared to MEA

Acknowledgement: * Pilot project partner RWE
Solutions for Large Scale PCC Plant (1100 Mw \textsubscript{el} Power)

**Design challenges**

Optimizing CAPEX by reduced number of trains to handle 18,000 tpd CO\textsubscript{2}
- 2 process trains selected
- reduced plot space

**Compressor section**
- two lines per train
  - flexible turn down operation

Lower number of trains results in bigger size of components, e.g.
- Absorption column: diameter ca. 18 m, height ca. 75 m  \rightarrow  on site fabrication required
- Pipes ducts and valves: diameters up to 7 meters
- Plot: ca. 100 m x 260 m
Concepts for a Large Scale PCC Plant
Key elements of plant costs

Main challenges
— Large equipment size requires new concepts
— Required plot area is very significant
— Alternative materials need to be assessed
— New equipment arrangements needed
— Field fabrication
— Large pipe and duct

Linde studies to address challenges
— Scaling to a very large single train
— Optimize equipment arrangement (flue gas blower, pre-cooler, absorption columns sump etc)
— Develop new column construction materials
— Optimize machinery options
Linde-BASF advanced PCC plant design*

Advanced emission control system

High capacity structured packing

Advanced Column Material & Design

Optimized Blower Concept

Gravity Flow Interstage Cooler

Optimized Energy Consumption

Higher Desorption Pressure

Optional Interstage Heater

Treated flue gas to stack

Flue gas blower

Make-up water

Water Cooler

Absorber

Interstage Cooler

Solvent Filter

Solvent Cooler

Water Wash

Desorber

RichLean Solvent Hex

Reboiler

Condensate return

LPMP_Steam

LP_Steam

Condensate

Separator

Condenser

CO2 to Compression

NaOH Tank

Cooler

DCC

Flue gas

Optimal Applications 2010-2012

## Project progress and accomplishments

<table>
<thead>
<tr>
<th>Task#</th>
<th>Task Description</th>
<th>Key Objectives</th>
<th>Accomplishments</th>
</tr>
</thead>
</table>
| 1     | Program Management | Complete project management plan and implement to agreed cost and schedule. | - Project kick-off meeting held  
- Updated project management plan completed |
| 2     | Techno-economic evaluation | Complete techno-economic analysis on a 550 MWe coal-fired power plant incorporating Linde-BASF PCC technology. | - Techno-economic assessment completed and presented to DOE-NETL |
| 3     | Pilot plant optimization and basic design | Define pilot plant design basis and the key features incorporated. Complete basic design and engineering. | - Design basis document completed and pilot plant features selected.  
- Basic design and engineering completed. |
| 4     | Pilot plant system design and engineering | Complete detailed design and engineering of the pilot plant (ready to build). | - Preliminary 3-D model developed  
- Detailed engineering in progress (30% model) |
| 5     | Pilot plant cost and safety analysis | Complete preliminary environment, health and safety assessment for the pilot plant | - Preliminary NEPA document completed.  
- Hazop review completed and design updates incorporated. |
Basis for techno-economic assessment for 550 MWₑ power plant with 90% CO₂ capture

Specifications and Design Basis

- Bituminous Illinois #6 Coal Characteristics
- Site Characteristics and Ambient Conditions
- Pulverized Coal Boiler Design
- Subcritical Steam Turbine Design
- Steam Cycle Conditions
- Environmental Controls and Performance
- Balance of Plant
- Economic Assumptions and Methodology

Computational Platform

UniSim Design Suite R390, integrated with
- Brian Research & Engineering ProMax® software for PCC parametric optimization
- BASE’s proprietary package for rigorous solvent performance predictions
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
Comparative PCC Performance Results
Linde-BASF vs Reference DOE/NETL Case*

Energy demand for different PCC plants

<table>
<thead>
<tr>
<th>Specific energy demand elements</th>
<th>NETL-MEA</th>
<th>Linde-BASF PCC (LB-1)</th>
<th>Linde-BASF PCC (LB-2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reboiler Duty</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
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<tr>
<td>Cooling Duty</td>
<td>70%</td>
<td>70%</td>
<td>70%</td>
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<tr>
<td>Electrical Power</td>
<td>40%</td>
<td>40%</td>
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</table>

Effect of PCC technology improvements on incremental energy requirement for power plant with CO2 capture and compression

Incremental fuel requirement for CO2 capture and compression

<table>
<thead>
<tr>
<th>NETL-MEA</th>
<th>Linde-BASF PCC (LB-1)</th>
<th>Linde-BASF PCC (LB-2)</th>
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<tbody>
<tr>
<td>0%</td>
<td>60%</td>
<td>40%</td>
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</table>

*Reference Case # 10 of DOE-NETL 2007/1281 Report
Total PCC Plant Cost

Significantly reduced total PCC plant Cost relative to DOE/NETL 2007 Reference Case #10 due to:

1. Reduced coal combustion (CO2 production) for 11.1% (LB-1) or 15.2% (LB-2)
2. Single train PCC design
3. Optimized PCC plant design
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**

- NETL - MEA: 24.9%
- Advanced Solvent: 1.76%
- PCC Optimization (LB-1): 1.39%
- Heat and Power Integration (LB-2): 1.35%
- LINDE-BASF (LB-2): 29.4%

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

- NETL - MEA: $119.6
- Advanced Solvent: $5.5
- Process Enhancements: $5.1
- PCC Optimization (LB-1): $5.5
- Heat and Power Integration (LB-2): $2.3
- LINDE-BASF: $101.2

Detailed Engineering Model of Pilot Plant

- Free-standing absorber and stripper
- Equipment modules containing pumps, blower, HX etc

Pilot plant located in NCCC site with the existing 0.5 MWe pilot and piperack in the background
Summary and Next Steps

- Linde and project partners are designing and building a 1 MWe post-combustion capture pilot plant to be installed and tested at the National Carbon Capture Center in Wilsonville, AL.
- The plant will incorporate BASF’s OASE® blue solvent technology and Linde-BASF process enhancements and demonstrate that target performance can be achieved.
- Techno-economic assessment on a 550 MWe coal-fired power plant has confirmed the significant energy and capex savings compared to a reference MEA PCC plant, thereby, driving down the levelized cost of electricity.
- Critical next steps for the project:
  - Complete detailed engineering of the pilot plant and firm cost estimates and reach “Go” decision to proceed pilot plant procurement and build (Budget Period 1)
  - Procure, fabricate and install pilot plant at the NCCC and achieve mechanical completion (Budget Period 2)
  - Perform parametric and long duration tests and confirm achievement of target performance. (Budget Period 3)
Acknowledgement and Disclaimer

Acknowledgement: This presentation is based on work supported by the Department of Energy under Award Number DE-FE0007453.

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Thank you for your attention!

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