Pilot plant demonstration of an advanced amine-based post-combustion capture technology for CO$_2$ capture from power plant flue gases

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The Linde Group Overview
Fully integrated gases and engineering company

Founded | 1879
Sales    | ~$21 billion
Employees| ~63,000
Countries| >100

Leveraging
Synergies

Linde Engineering
Technology-focused

Air Separation | Hydrogen/Syn Gas
Global #1       | Global #2

Olefins | Natural Gas
Global #2      | Global #3

Linde Gas - Tonnage
World-class operations

HyCO Tonnage Plants | ASU Tonnage Plants
>70 plants          | >300 plants

CO2 Plants | Packaged Std Plants
>100 plants  | >1,000 plants
## Linde offers technology and engineering solutions for all three CCS pathways

<table>
<thead>
<tr>
<th>Technology</th>
<th>Process</th>
<th>Linde Portfolio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre-combustion</strong></td>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
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<td><strong>Oxyfuel</strong></td>
<td><img src="image3.png" alt="Diagram" /></td>
<td><img src="image4.png" alt="Diagram" /></td>
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<tr>
<td><strong>Post-combustion</strong></td>
<td><img src="image5.png" alt="Diagram" /></td>
<td><img src="image6.png" alt="Diagram" /></td>
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</tbody>
</table>
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)
Commercial references
Linde has a long experience in the field of CO₂ handling

**CO₂ Capture and injection**
- LNG plant for Statoil in Snøhvit/Norway with CO₂ capture from natural gas and CO₂ re-injection offshore

**CO₂ Wash Units**
- Experience in design and erection of different wash processes for CO₂ removal
  - Linde-Rectisol ®
  - BASF Oase technology ®
  - Benfield

**CO₂ Food Grade Plants**
- Removal of impurities like Hydrocarbons, Heavy metals, O₂, H₂O for food grade CO₂

**CO₂ Transport and distribution**
- Long experience in operation of CO₂ plants, transport and distribution
  - OCAP pipeline (Netherlands)
  - Onsite business
  - Bulk supply
BASF OASE® blue Technology Development
Adopted and optimized for PCC applications

Equilibria

Kinetics

Stability

Lab scale
— Ludwigshafen, Germany
— Advanced solvent screening, development, optimization

Mini plant
— Ludwigshafen, Germany
— Solvent performance verification

Pilot: 0.45MWe
— 2009, Niederaussem
— Process opt., materials & emissions testing

Pilot: 1.5 MWe
— 2014, Wilsonville, AL
— Design improvements, emissions confirmation
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

Operation key figures within 1.5 years of operation:
- >10,000 hours operation
- 2500 t CO₂ captured
Pilot Plant Niederaussem
Phase 2 focus: Long term testing, solvent degradation and emissions reduction

Status: Phase I and II (Dec 2013)
- > 26,000 hours operation
- > 7200 t CO₂ captured
- availability: 97%

Test period - phase I und II [h]

10/9/2014
Linde-BASF novel amine-based PCC technology features

- Advanced emission control system
- High capacity structured packing
- Optimized Blower Concept
- Gravity Flow Interstage Cooler
- Optimized Energy Consumption
- Unique reboiler design
- Make-up water
- Absorber
- Interstage Cooler
- Condenser
- Desorber
- Higher Des. Pres. & Interstage Heater
- Reboiler
- Solvent Tank
- Treated flue gas
- CO₂
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
- NETL-MEA
- Linde-BASF PCC (LB-1)
- Linde-BASF PCC (LB-2)

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

Specific energy demand elements:
- Reboiler Duty
- Cooling Duty
- Electrical Power

Incremental fuel requirement for CO₂ capture and compression:
- NETL-MEA
- Linde-BASF PCC (LB-1)
- Linde-BASF PCC (LB-2)

*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

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

Module design:

1. Six equipment modules (approximately 30 ft x 13 ft x 9 ft).
2. Arranged in three levels, two side by side at each level.
3. Design was to maximize shop fabrication. Off module piping produced by module fabricator.
4. Steel structure above the top module to support absorber (prevent swaying, 90 miles/hr wind design basis)
Columns fabrication in the shop in Decatur, Alabama

Absorber section in fabrication and assembly

- Stripper column fabrication and internals assembly completed. Shipment to site as one piece.
- Absorber columns section fabrication and internals assembly completed. Shipment to site in three sections.
- Absorber column packing and internals for the bottom two sections installed at site.

Stripper section in fabrication and assembly
Site prepared and ready to install equipment and modules (Jan 10, 2014)
First of 6 modules set in position
Analytical container set in place (left) and module installation completed (right)
Analytical container fabricated in shop and installed at site

- Pilot plant incorporates significant instrumentation and online analytical measurements

- Batch analysis in conjunction with online measurements allow redundancy checks for mass and energy balances

- Batch sampling and offsite analysis for solvent stability measurements

- Corrosion coupons incorporated to assess effect on materials over the testing duration
Stripper column delivery and installation at site
Absorber bottom section ready for installation
Top section of the absorber lifted into position (left); Column installation complete (right)
Current project status and plans

- Mechanical completion of the 1 MW_e pilot plant achieved on July, 2014
- Pre-start up safety review and comprehensive system installation checks against P&ID and design intent performed to identify issues to address prior to start up
- Machine start-up and water recirculation tests were performed in August 2014 to establish functionality and operability of system components.
- Solvent loading and system initial start-up is planned for end November-early December 2014.
- Following stable operations, parametric testing and long duration testing will be implemented.
Summary and conclusions

— Linde and BASF are partnering in the development of an advanced PCC technology incorporating BASF’s novel amine-based process along with Linde's process and engineering innovations
— Performance demonstrated and long term stability validated on a 0.45 MWe lignite fired power plant flue gases
— Nominal 1 MWe pilot plant in Wilsonville, AL mechanically complete and ready for initiating tests
— Techno-economic evaluation has shown that technology offers significant benefits:
  — Optimized solvent results in lower regeneration energy and long term stability
  — Unique process options and large single train capacity plant implementation with lowered capex
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Thank you for your attention!

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