Pilot plant demonstration of an advanced amine-based post-combustion capture technology for CO_2 capture from power plant flue gases

Torsten Stoffregen, Sean Rigby, Stevan Jovanovic and Krish Krishnamurthy

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THE LINDE GROUP

Linde

The Linde Group Overview

Fully integrated gases and engineering company

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

Linde Engineering

Technology-focused

Air Separation

Global #1

Hydrogen/Syn Gas

Global #2

Olefins

Global #2

Natural Gas

Global #3

Leveraging Synergies

Linde Gas - Tonnage

World-class operations

HyCO Tonnage Plants

>70 plants

ASU Tonnage Plants

>300 plants

CO2 Plants

>100 plants

Packaged Std Plants

>1,000 plants

Linde offers technology and engineering solutions for all three CCS pathways

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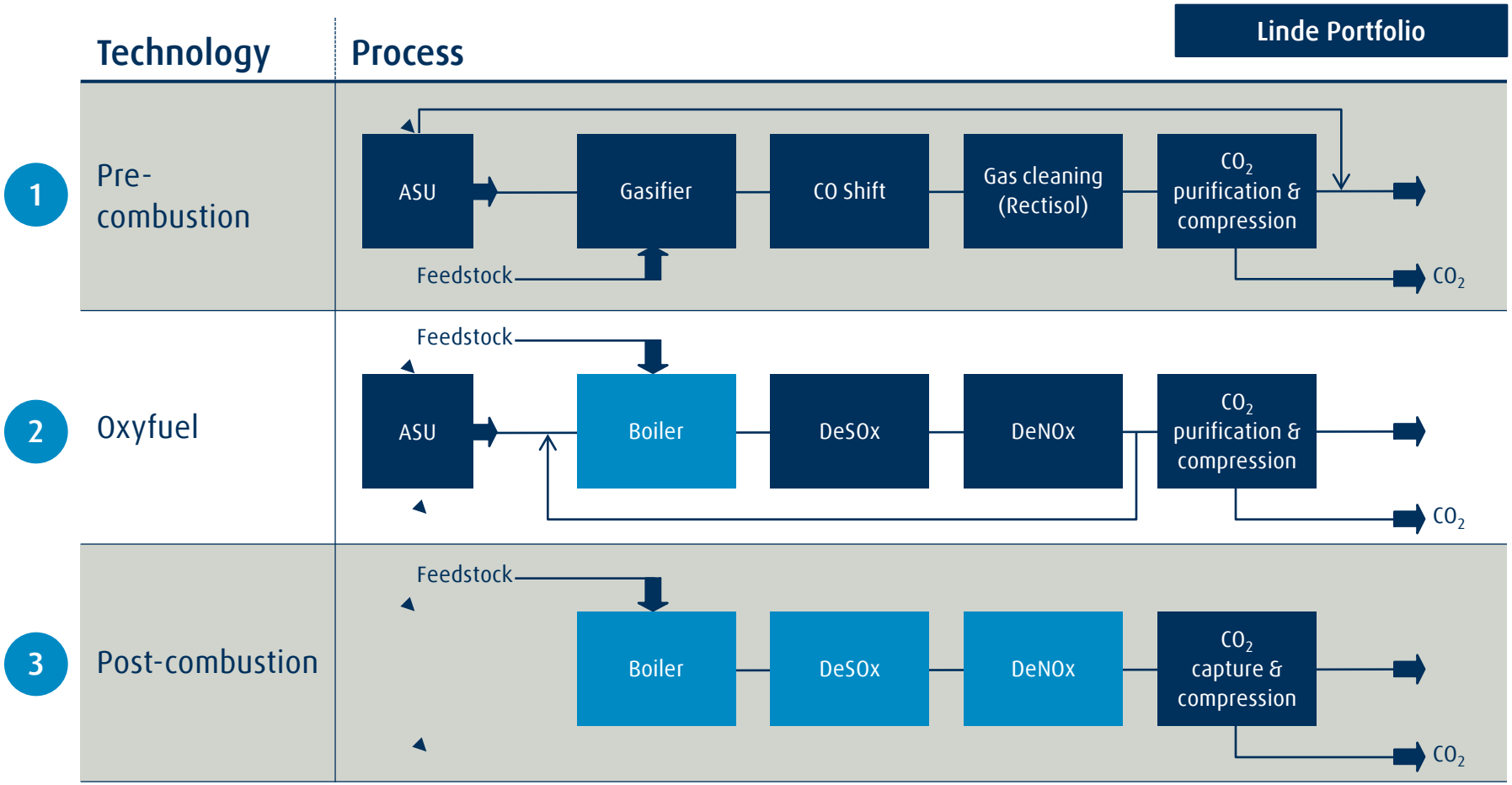

Project Overview: Key Drivers

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- Post-combustion CO_2 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 CO_2 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 CO_2 handling

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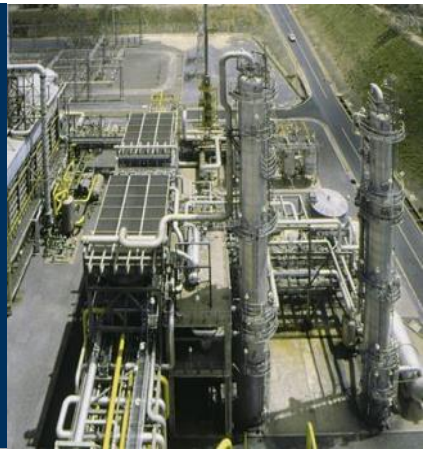
CO_2 Capture and injection

LNG plant for Statoil in Snøhvit/Norway with CO_2 capture from natural gas and CO_2 re-injection off-shore

CO_2 Wash Units

Experience in design and erection of different wash processes for CO_2 removal

- Linde-Rectisol ®
- BASF Oase technology ®
- Benfield



CO_2 Food Grade Plants

Removal of impurities like Hydrocarbons, Heavy metals, O_2, H_2O for food grade CO_2

CO_2 Transport and distribution

Long experience in operation of CO_2 plants, transport and distribution

- OCAP pipeline (Netherlands)
- Onsite business
- Bulk supply

BASF OASE® blue Technology Development

Adopted and optimized for PCC applications

BASF The Chemical Company

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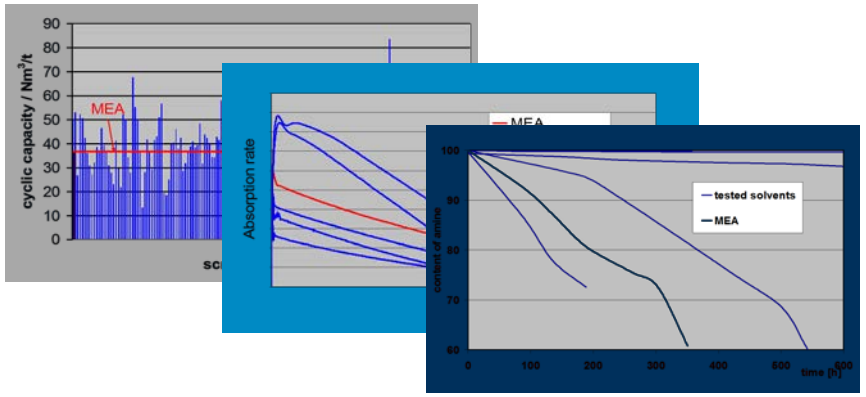
Equilibria

Kinetics

Stability



Lab scale	Mini plant	Pilot: 0.45MWe	Pilot: 1.5 MWe
— Ludwigshafen, Germany — Advanced solvent screening, development, optimization	— Ludwigshafen, Germany — Solvent performance verification	— 2009, Niederaussem — Process opt., materials & emissions testing	— 2014, Wilsonville, AL — Design improvements, emissions confirmation

Niederaussem Pilot Plant: Main results of Phase I

RWE The energy to lead

BASF The Chemical Company

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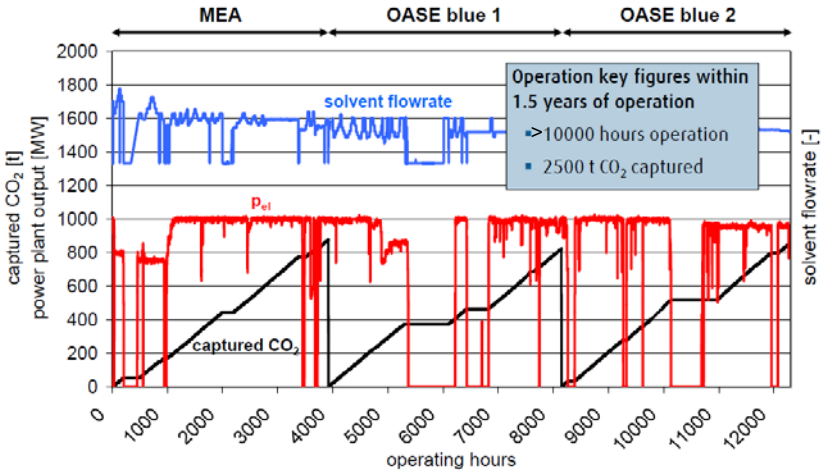
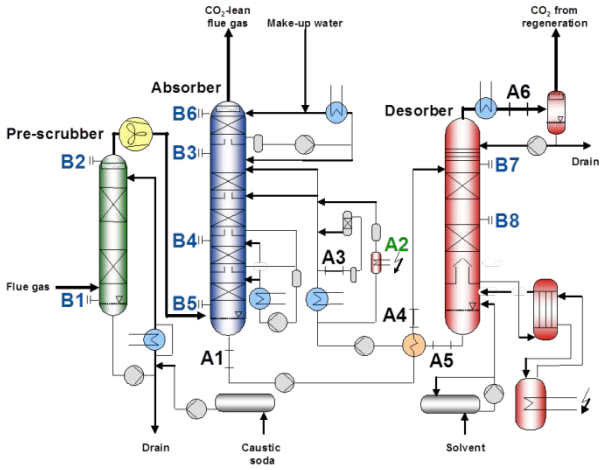
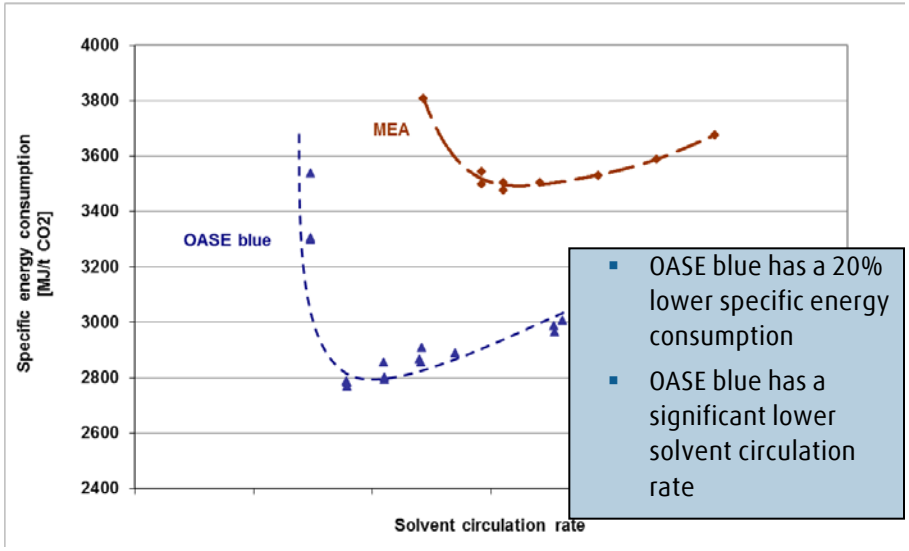




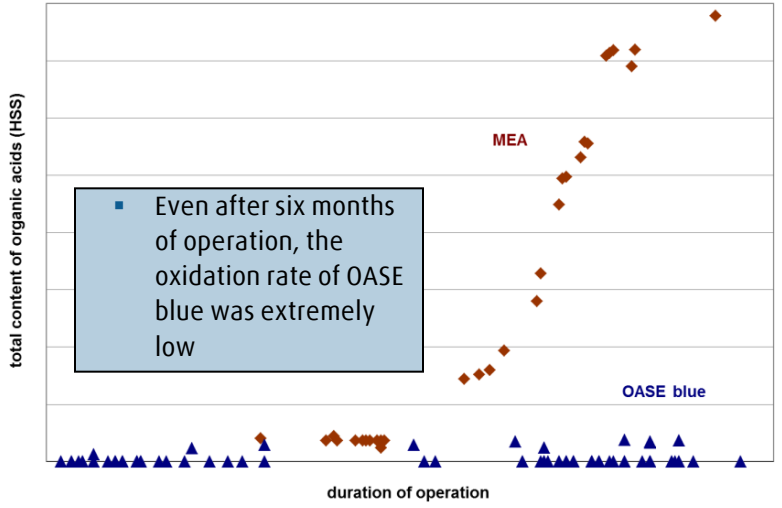
A1, A3 – A6:
Flanges, tubes, gaskets

A2:
Concrete module

B1 - B8
Coupons



- 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

Pilot Plant Niederaussem

Phase 2 focus: Long term testing , solvent degradation and emissions reduction

RWE The energy to lead

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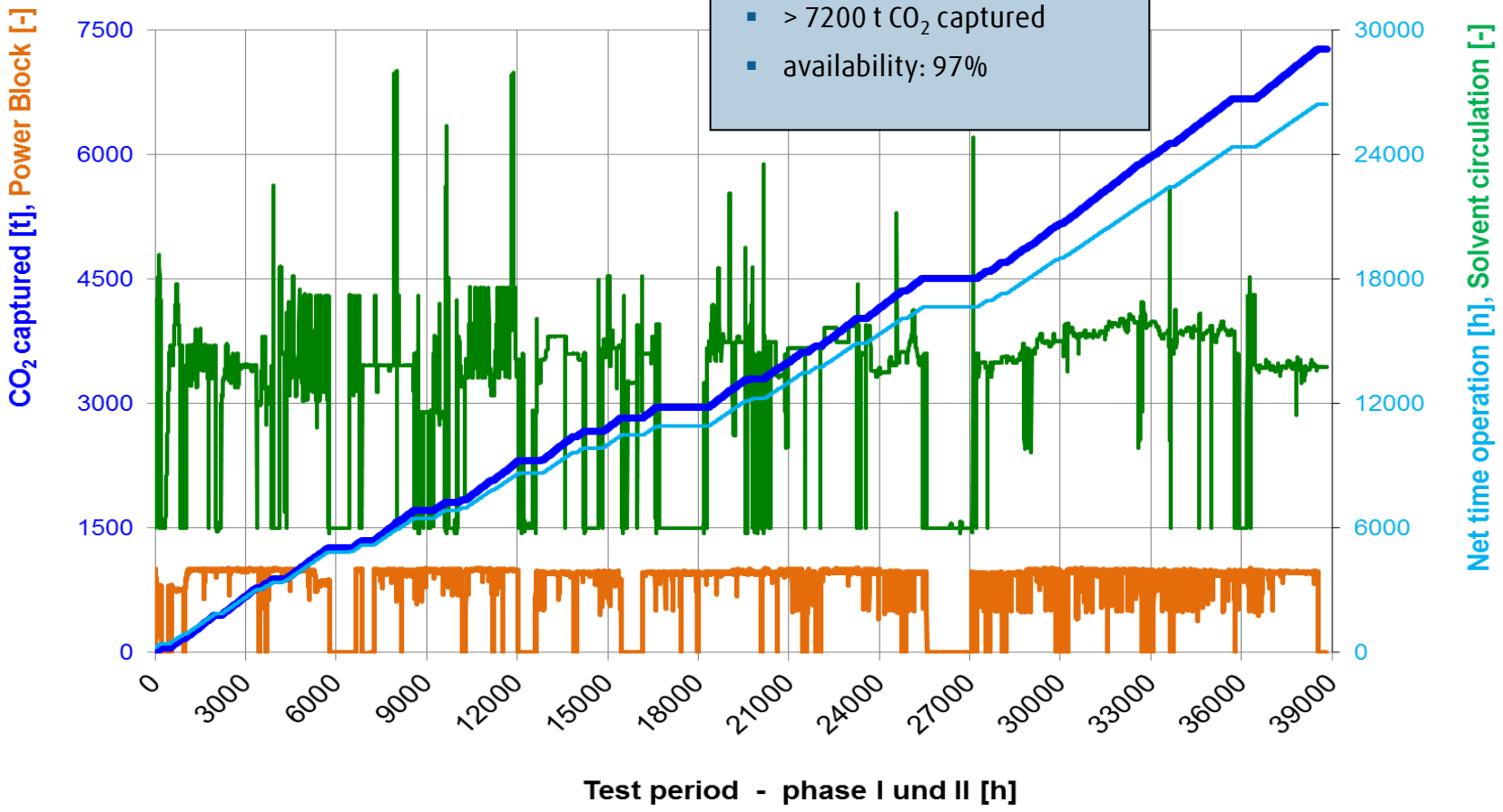
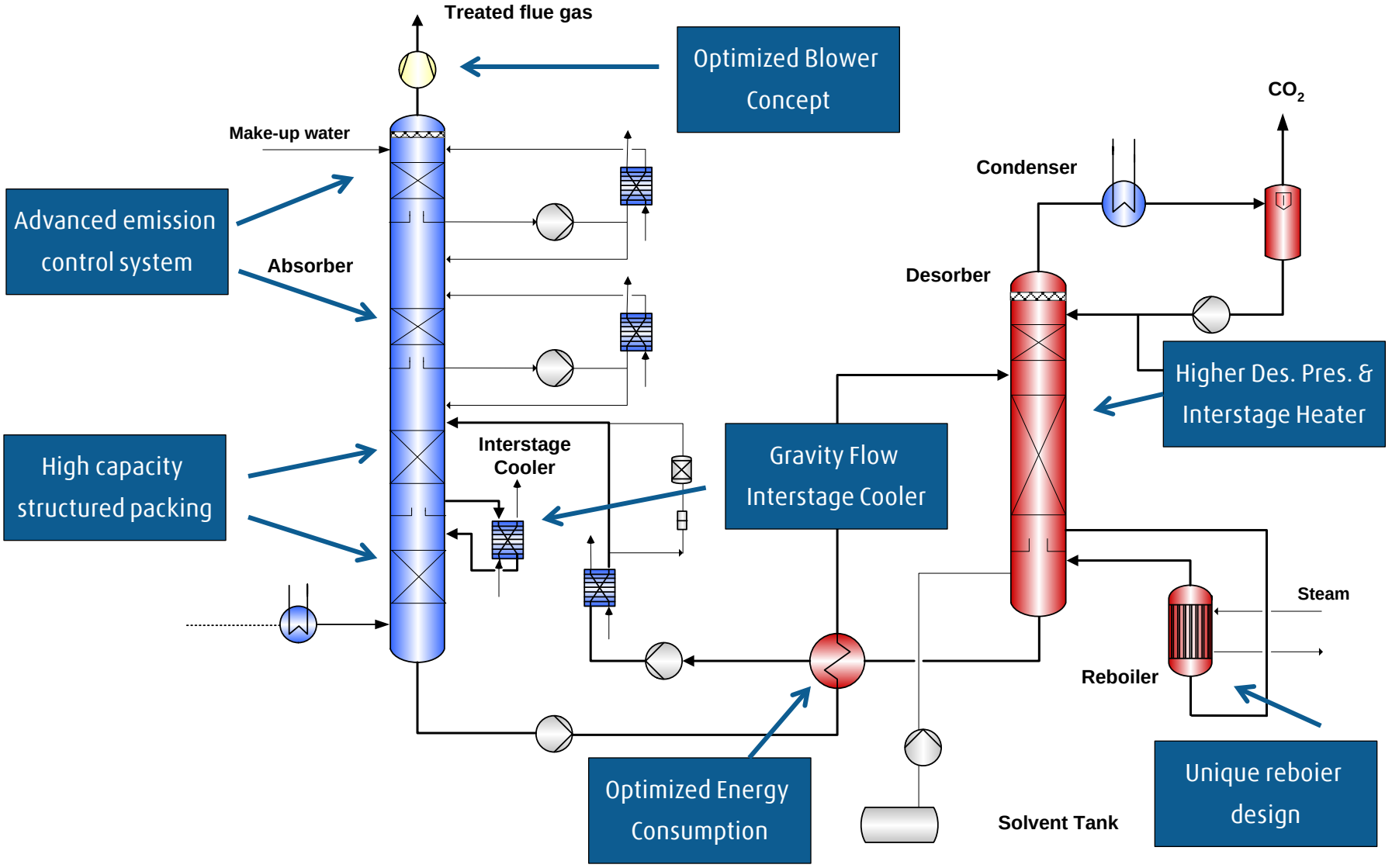
Status: Phase I and II (Dec 2013)

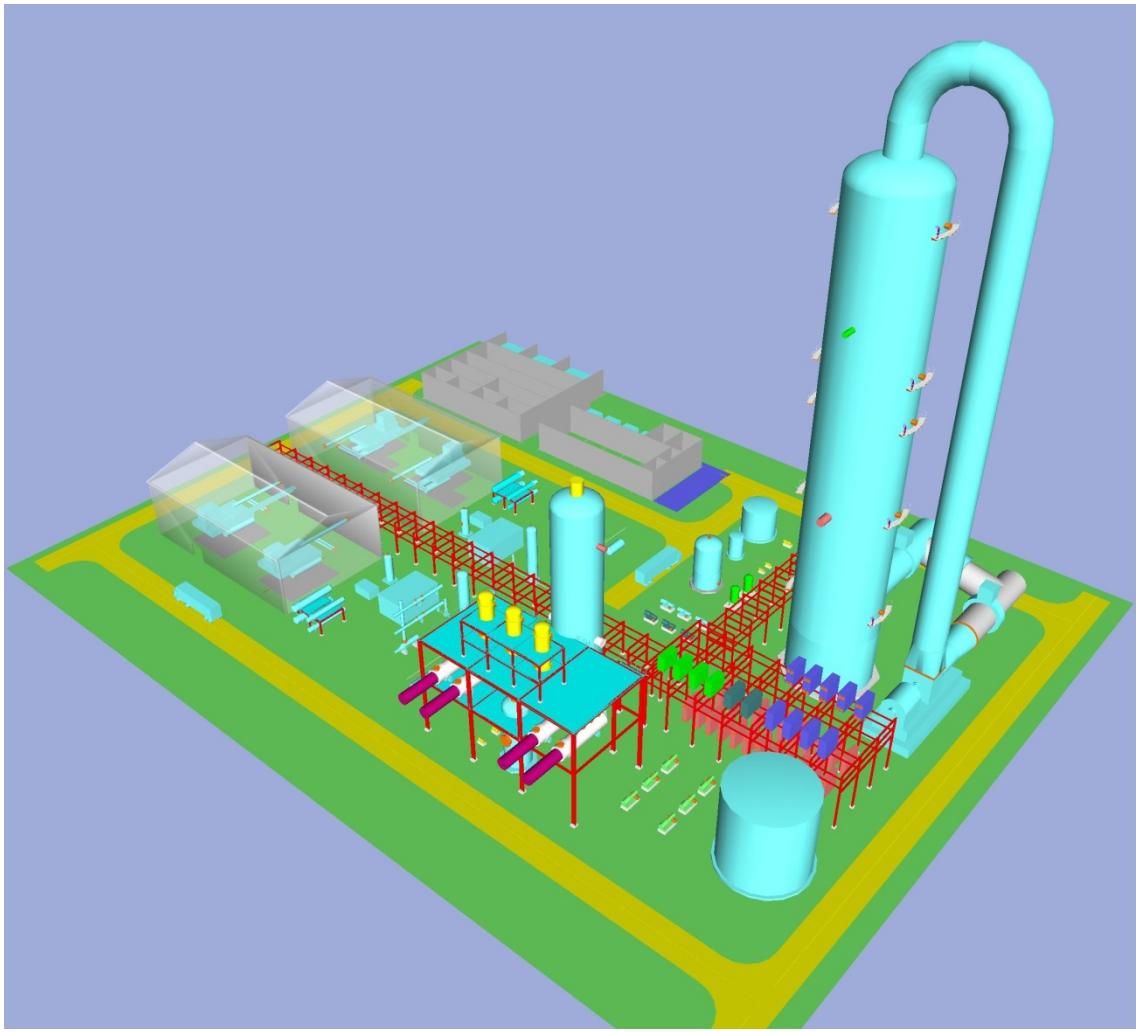
- > 26,000 hours operation
- > 7200 t CO_2 captured
- availability: 97%



Linde-BASF novel amine-based PCC technology features

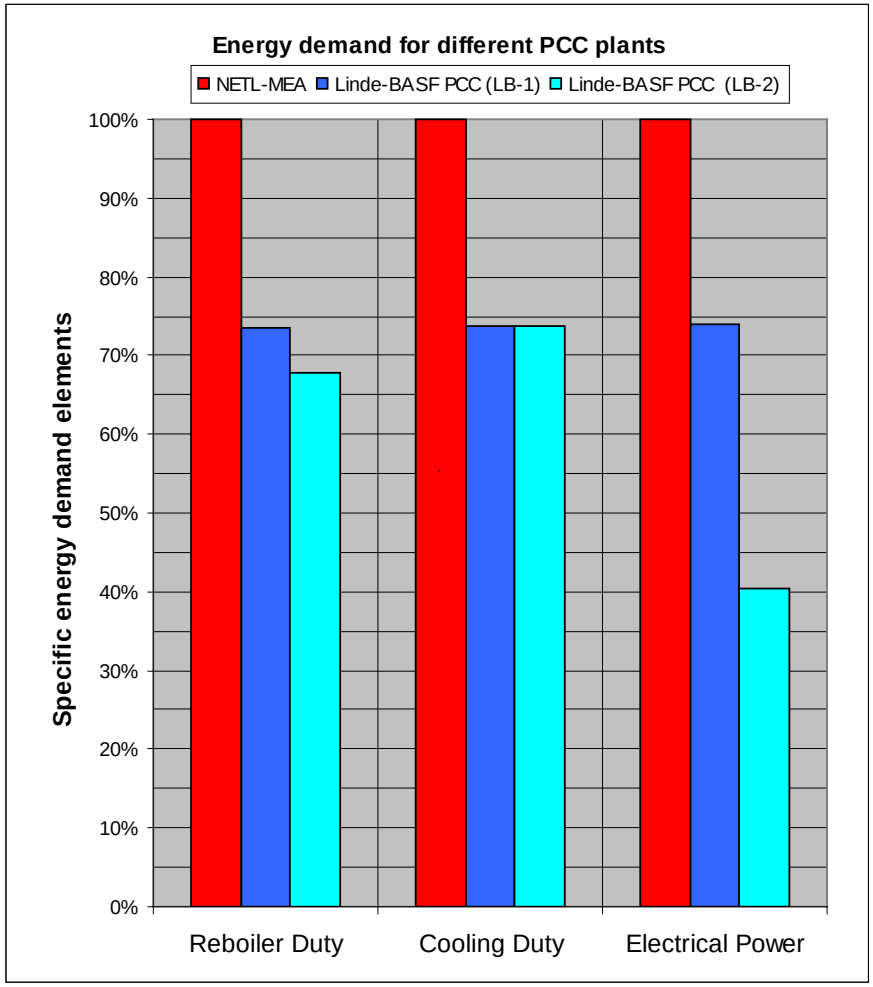


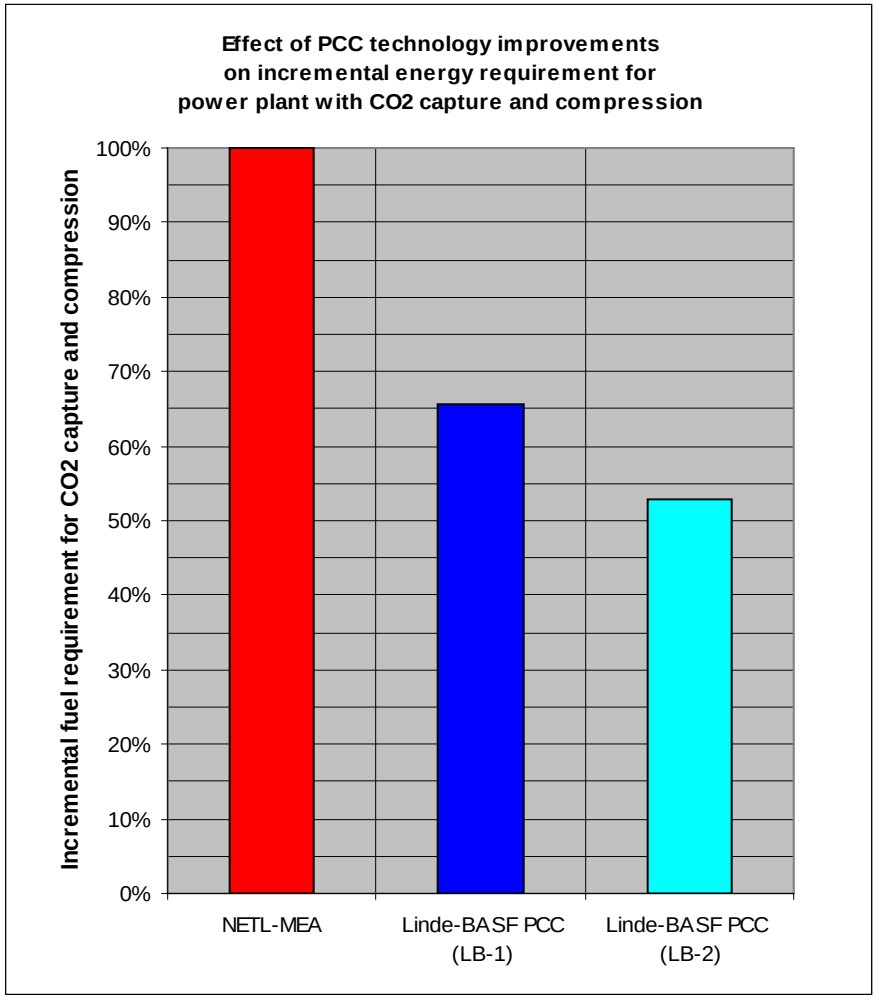
Linde-BASF PCC Plant Design for 550 MWe PC Power Plant



- Single train PCC design for ~ 13,000 TPD CO_2 capture
- 40-50% reduced plot area to 180m x 120 m

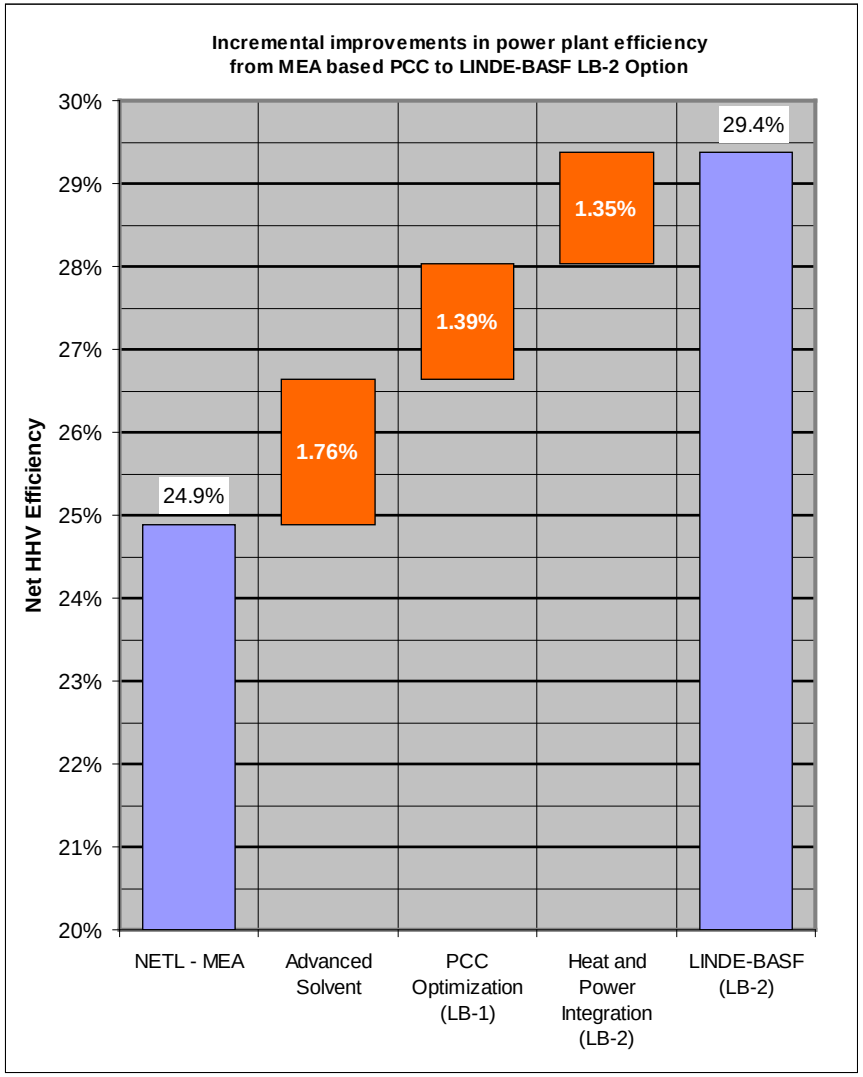
Comparative PCC Performance Results
Linde-BASF vs Reference DOE/NETL Case*

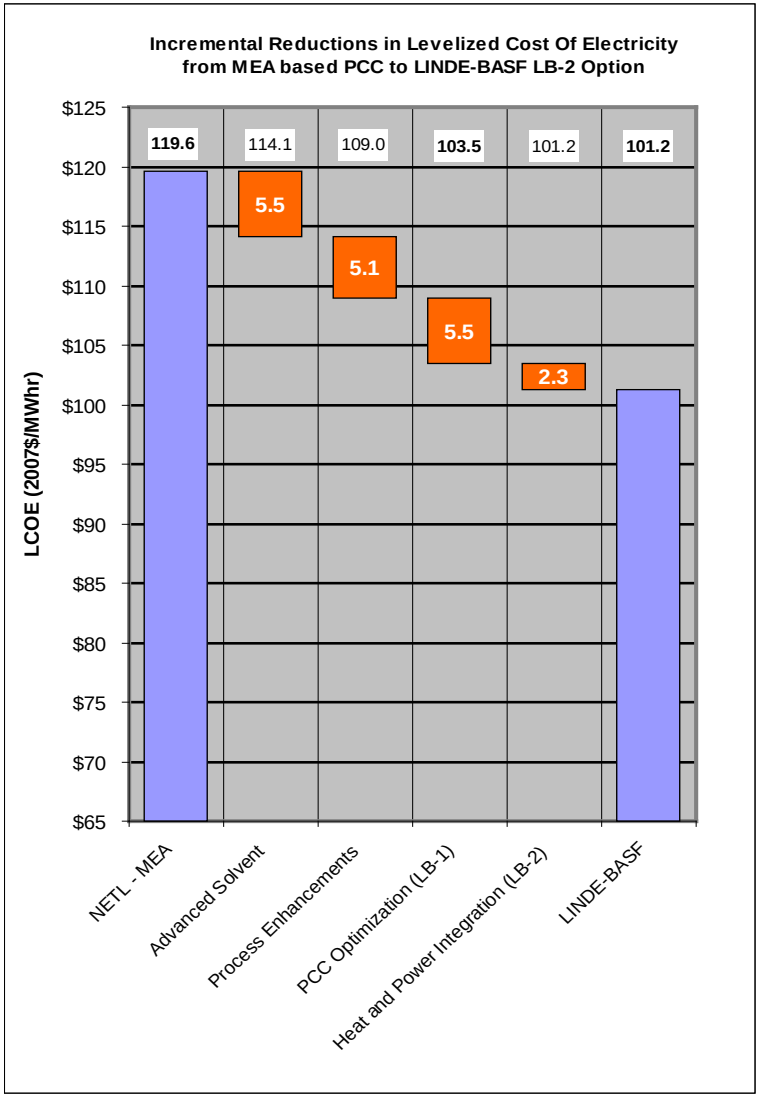




* Reference Case # 10 of DOE-NETL 2007/1281 Report

Power plant efficiency improvements and LCOE reductions with Linde-BASF PCC technology





Source: Project DE-FE0007453 Techno-economic analysis of 550 MWe PC power plant with CO2 capture, May 2012.

Module fabrication and installation in shop (Red Bud, IL)

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A single completed module

Module installation & Assembly

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

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Absorber section in fabrication and assembly

Stripper 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.

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

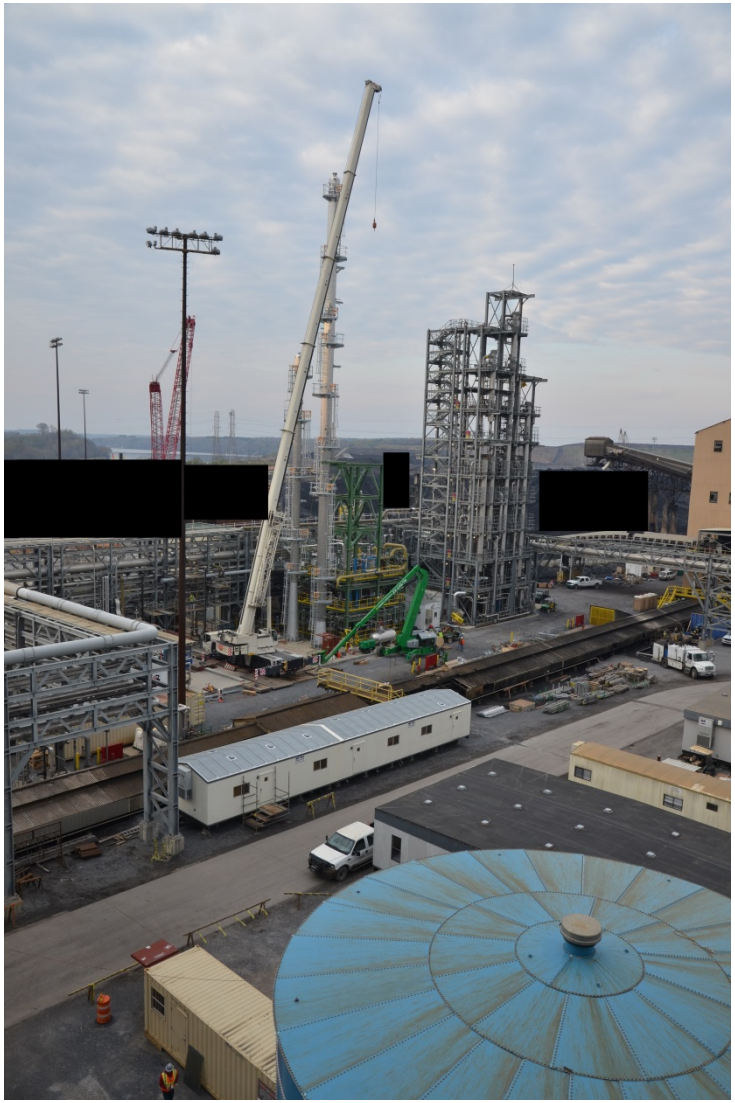
Analyzer and controls container

Analyzer and sampling panels

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.

Linde 1 MW_e pilot plant at the NCCC

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

Acknowledgement and Disclaimer

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Thank you for your attention!

Krish R. Krishnamurthy, Linde LLC
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