# 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

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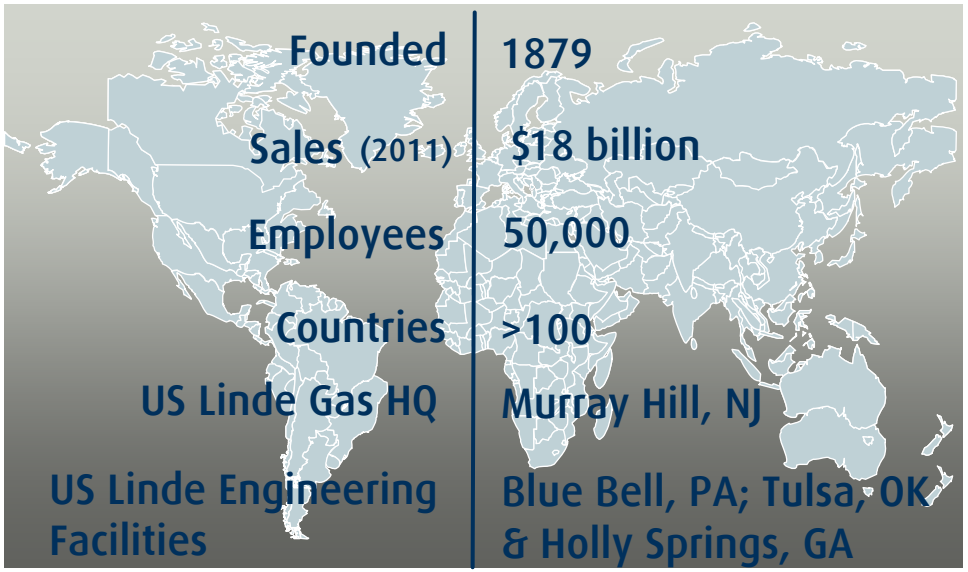
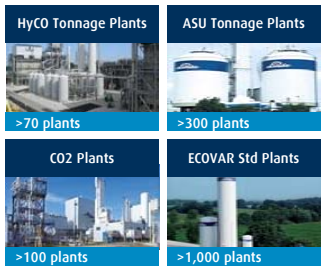


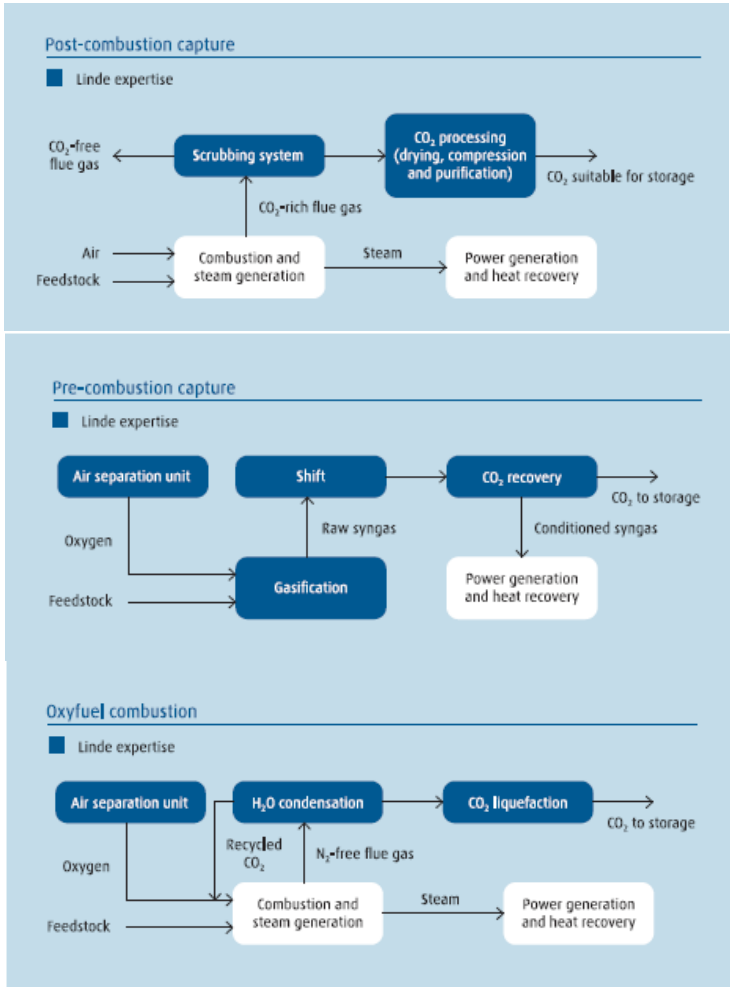

**Linde Engineering**
Technology-focused


Leveraging Synergies

**Linde Gas - Tonnage**
World-class operations




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



# Project Participants

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

# Project Objectives

## 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 $CO_2$ capture technology to illustrate the benefits

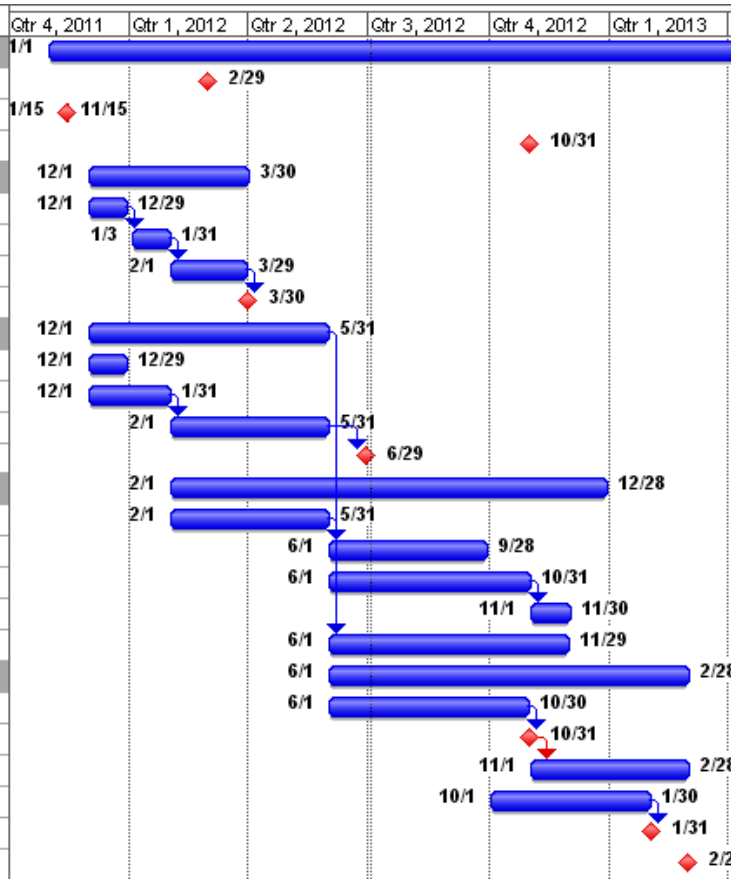
— Design, build and operate the 1MWel pilot plant at a coal-fired power plant host site providing the flue gas as a slipstream

— 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

| ID | Task Name |
|---|---|
| 1 | **1. Project management and planning** |
| 2 | **a. Submit project management plan** |
| 3 | **b. Conduct kick-off meeting** |
| 4 | **e. Host site agreement executed** |
| 5 | **2 Techno-economic evaluation on a 550 Mwel power plant** |
| 6 | 2.1 Basis and scope for power plant with CO2 capture and compression |
| 7 | 2.2 Detailed design of the power plant |
| 8 | 2.3 Economic analysis of the power plant with CO2 capture and compression |
| 9 | **c. Complete initial techno-economics analysis on a 550 MWe power plant** |
| 10 | **3 Pilot plant design optimization & basic design** |
| 11 | 3.1 Solvent selection and basic amine process design |
| 12 | 3.2 Parametric design optimization and confirmation of design basis |
| 13 | 3.3 Basic design package of the pilot plant |
| 14 | **d. Complete basic design and engineering of the 1 MWe pilot plant to be tested at the NCCC** |
| 15 | **4. Pilot plant system design and engineering** |
| 16 | 4.1 Preliminary engineering studies |
| 17 | 4.2 Process design review and HazOP |
| 18 | 4.3 Detailed design and engineering |
| 19 | 4.4 Development of equipment packages |
| 20 | 4.5 Site design, engineering and foundations specification |
| 21 | **5. Pilot plant cost and safety analysis** |
| 22 | 5.1 Preliminary pilot plant ES&H assessment |
| 23 | **f. Complete initial EH&S Assessment** |
| 24 | 5.2 Transportation and lifting study |
| 25 | 5.3 Cost estimation and updated pilot plant cost build up |
| 26 | **g. Complete pilot plant engineering and cost analysis for the 1 MWe unit to be tested at NCCC** |
| 27 | **Go - No Go decision to build pilot plant** |




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

| Source | Budget Period 1<br>Dec 2011 – Feb 2013 | Budget Period 2<br>Mar 2013 – Feb 2014 | Budget Period 3<br>Mar 2014 – Nov 2015 | Total |
|---|---|---|---|---|
| DOE Funding | $2,215,352 | $9,822,449 | $2,754,564 | $14,792,365 |
| Cost Share | $553,838 | $2,455,612 | $688,641 | $3,698,091 |
| Total Project | $2,769,190 | $12,278,061 | $3,443,205 | $18,490,456 |

Cost share commitments:

Linde: $3,107,352

BASF: $ 493,360

EPRI: $ 97,379

# Key Project Milestones (Budget Period 1)

**Budget Period 1 (Dec. 1, 2011 – Feb. 28, 2013)**

- 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 analyis for the 1 MWe pilot plant to be tested at NCCC (01/31/2013)

# Key Project Milestones (Budget Periods 2 and 3)

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**Budget Period 2 (Mar. 1, 2013 – Feb. 28, 2014)**

- 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

## $CO_2$ capture in natural gas processing: Re-injection Project - Hammerfest

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**World's first industrial project to deliver $CO_2$ 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

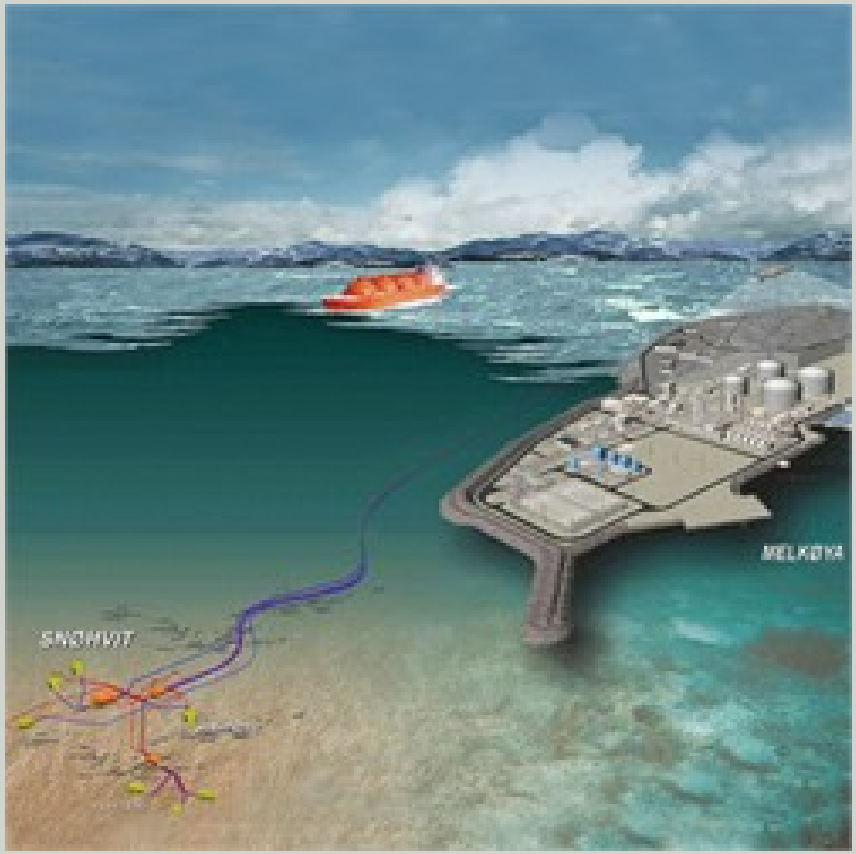
— $CO_2$ sequestration and re-injection integral part of the Hammerfest LNG project. **Linde performed design, EPC and commissioning**

— One dedicated well for $CO_2$ storage in a sandstone formation sealed by shale cap.

— Re-injection started in April 2008

— **BASF's OASE® purple process used in $CO_2$ capture**

**700,000 tpa $CO_2$ capture and re-injection (part of world scale LNG project, Snøhvit, Norway)**



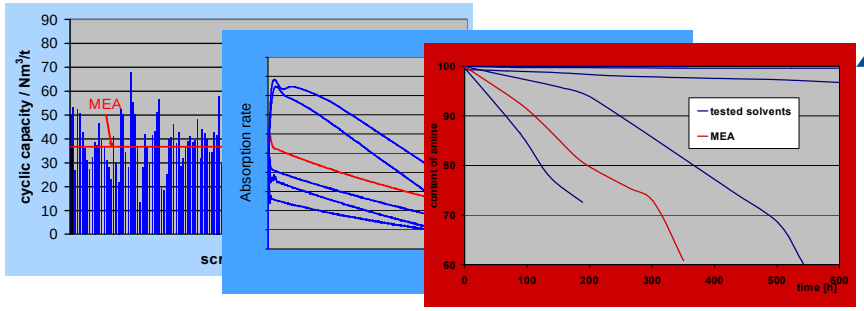
# Post combustion $CO_2$ capture: Challenges compared to $CO_2$ removal in NG/LNG plants

| | NG/LNG | Flue gas |
|---|---|---|
| Pressure | 50 – 100 bars | 1 bara |
| $CO_2$ partial pressure | 1 – 40 bars | 30 – 150 mbars |
| Flowrate | up to 60 mio scf/hr | up to 120 mio scf/hr |
| Gas composition | $CH_4$, $C_2H_6$, …, $CO_2$, $H_2S$, COS, $C_xH_y$,S, $H_2O$ | $N_2$, $O_2$, $H_2O$, $CO_2$, ($SO_x$) $NO_x$ |
| Treated gas specification | 50 ppm – 2 % $CO_2$<br>S < 4 – 10 ppm | $CO_2$ removal rate (90 %)<br>low amine emissions |
| Energy efficiency | not a key issue | of highest priority<br>$\eta \searrow$ 7-10% points |

- ❑ large volume flows @ low pressure
- ❑ solvent stability
- ❑ emissions of solvent
- ❑ overall power plant efficiency losses

# BASF OASE® blue Technology Development Designed for PCC Applications

Equilibr Kinetics Stability

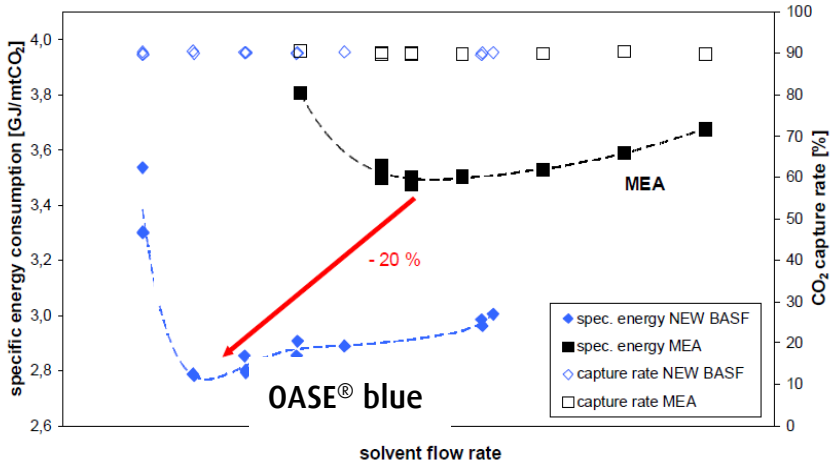


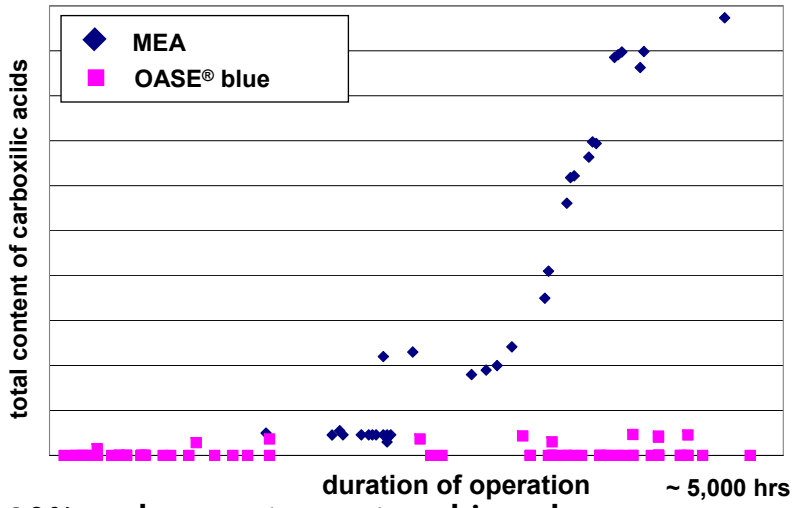

Fundamental Lab Scale R&D: Advanced Solvents Screening, Development, Optimization

BASF Miniplant, Ludwigshafen, Germany: Solvent Performance Verification

0.45 MWe PCC Pilot, Niederaussem, Germany: Preliminary Process Optimization

# Niederaussem* pilot plant 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 $Mw_{el}$ Power) Design challenges

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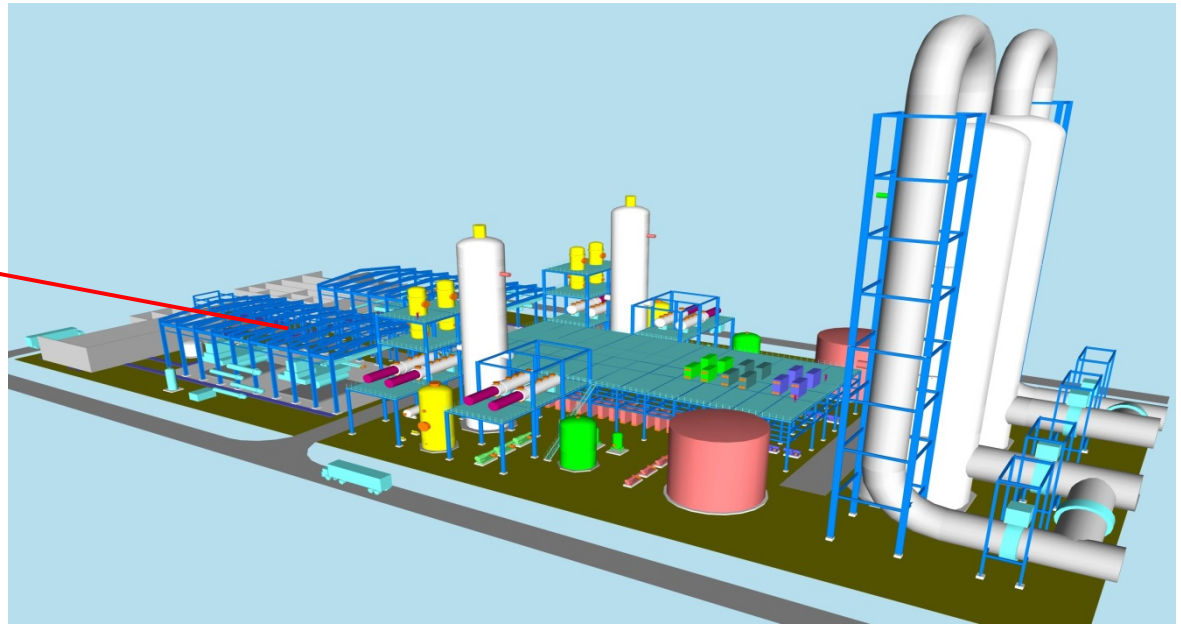
Optimizing CAPEX by reduced number of trains to handle 18,000 tpd $CO_2$

- 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 → 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

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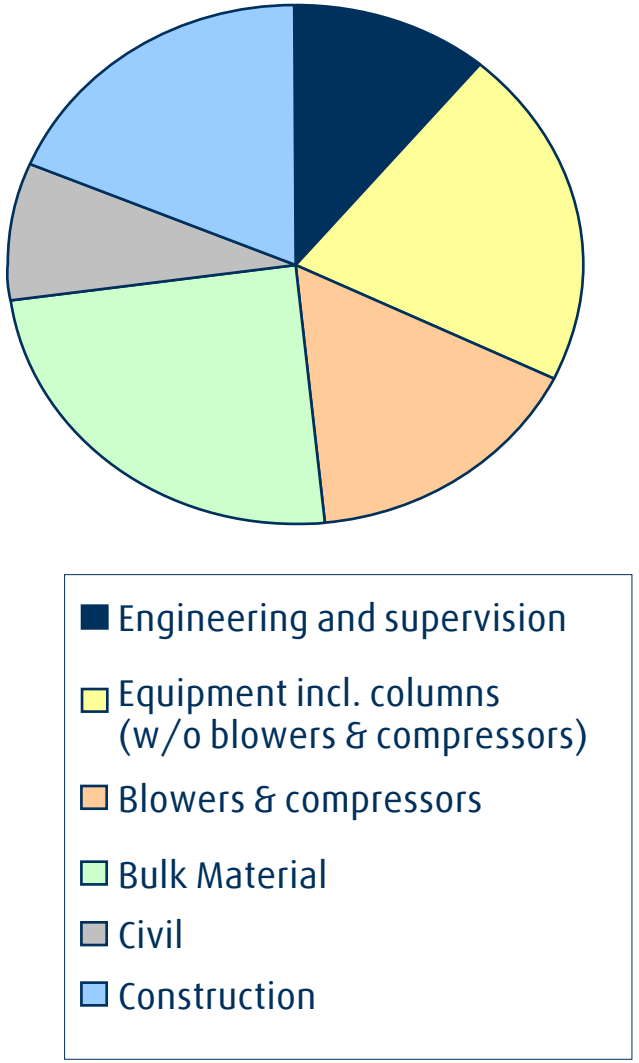
## Main challenges

- 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

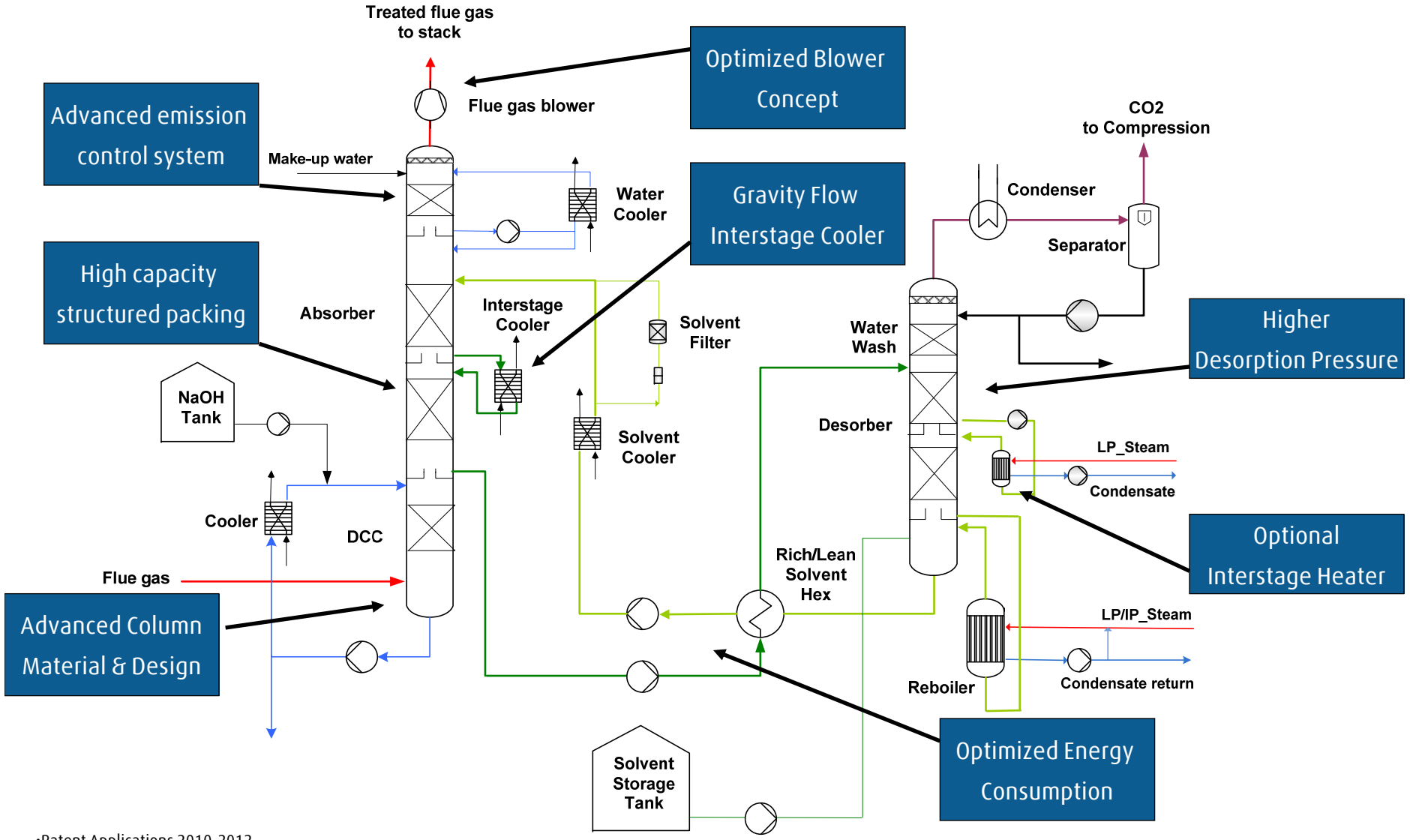
## Linde studies to address challenges

- 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

## Total plant cost distribution



# Linde-BASF advanced PCC plant design*




•Patent Applications 2010-2012

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

# Project progress and accomplishments

| Task# | Task Description | Key Objectives | Accomplishments |
|---|---|---|---|
| 1 | Program Management | Complete project management plan and implement to agreed cost and schedule. | - Project kick-off meeting held<br>- 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.<br>- 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<br>- 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.<br>- Hazop review completed and design updates incorporated. |

# Basis for techno-economic assessment for 550 $MW_e$ power plant with 90% $CO_2$ capture

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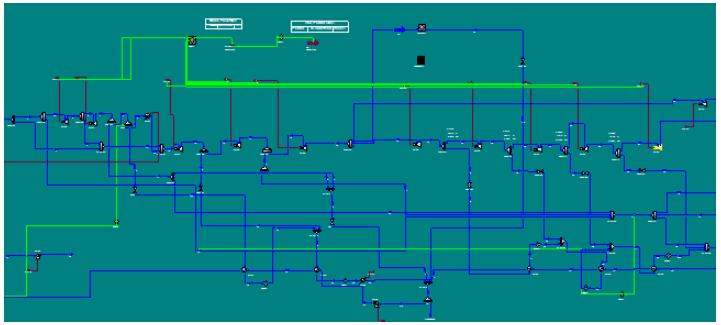
## Specifications and Design Basis

identical to DOE/NETL Report 2007/1281

as per DE-FOA-0000403 requirements

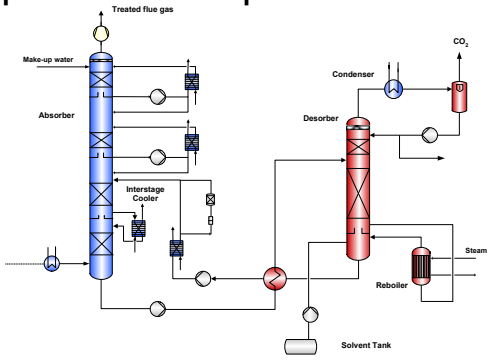
- Bituminous Illinois #6 Coal Characteristics
- Site Characteristics and Ambient Conditions
- Pulverized Coal Boiler Design
- Subcritical Steam Turbine Design
- Steam Cycle Conditions
- Environmental Controls and Performance
- Balance of Plant
- Economic Assumptions and Methodology

## Computational Platform

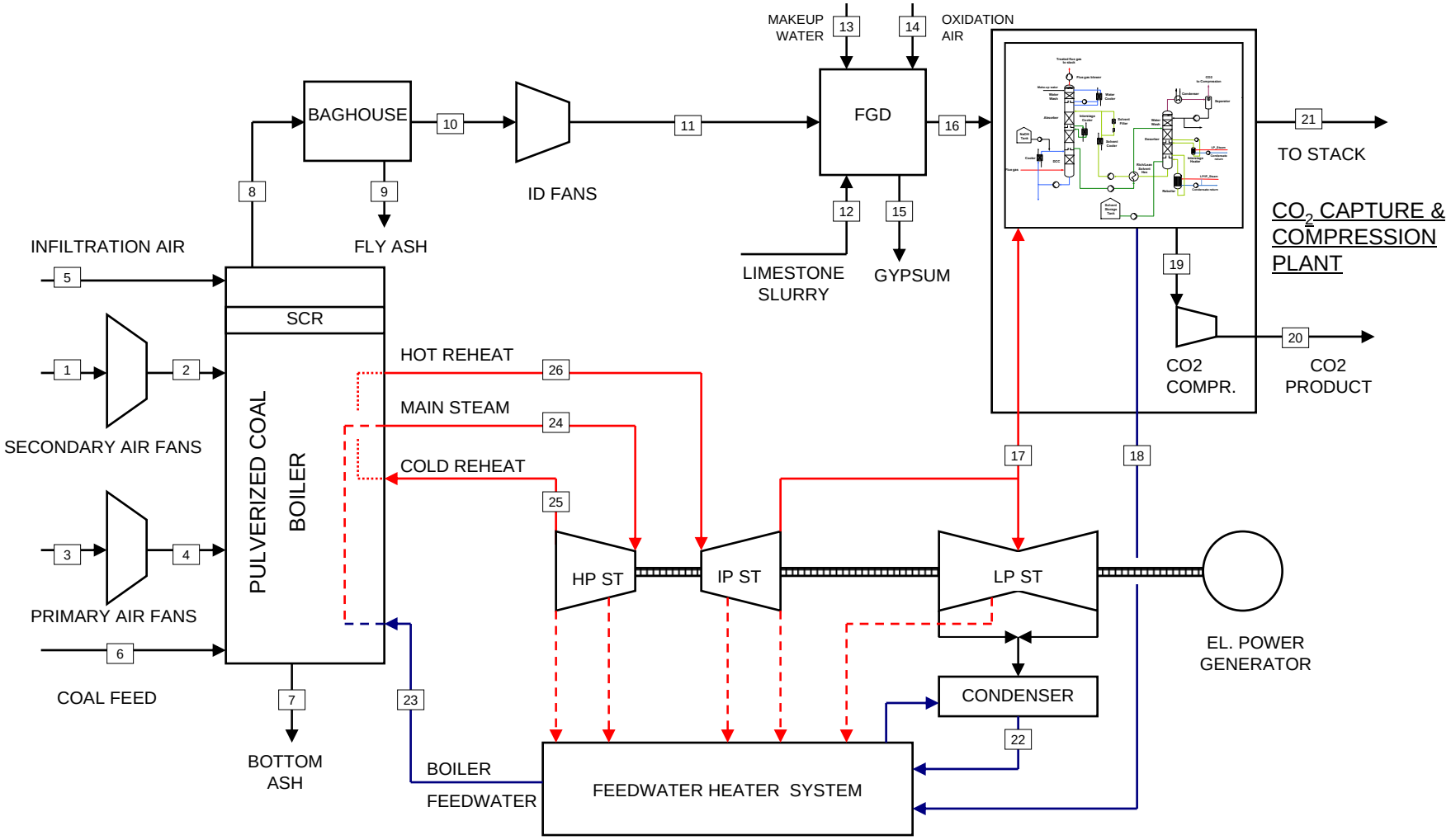


UniSim Design Suite R390, integrated with

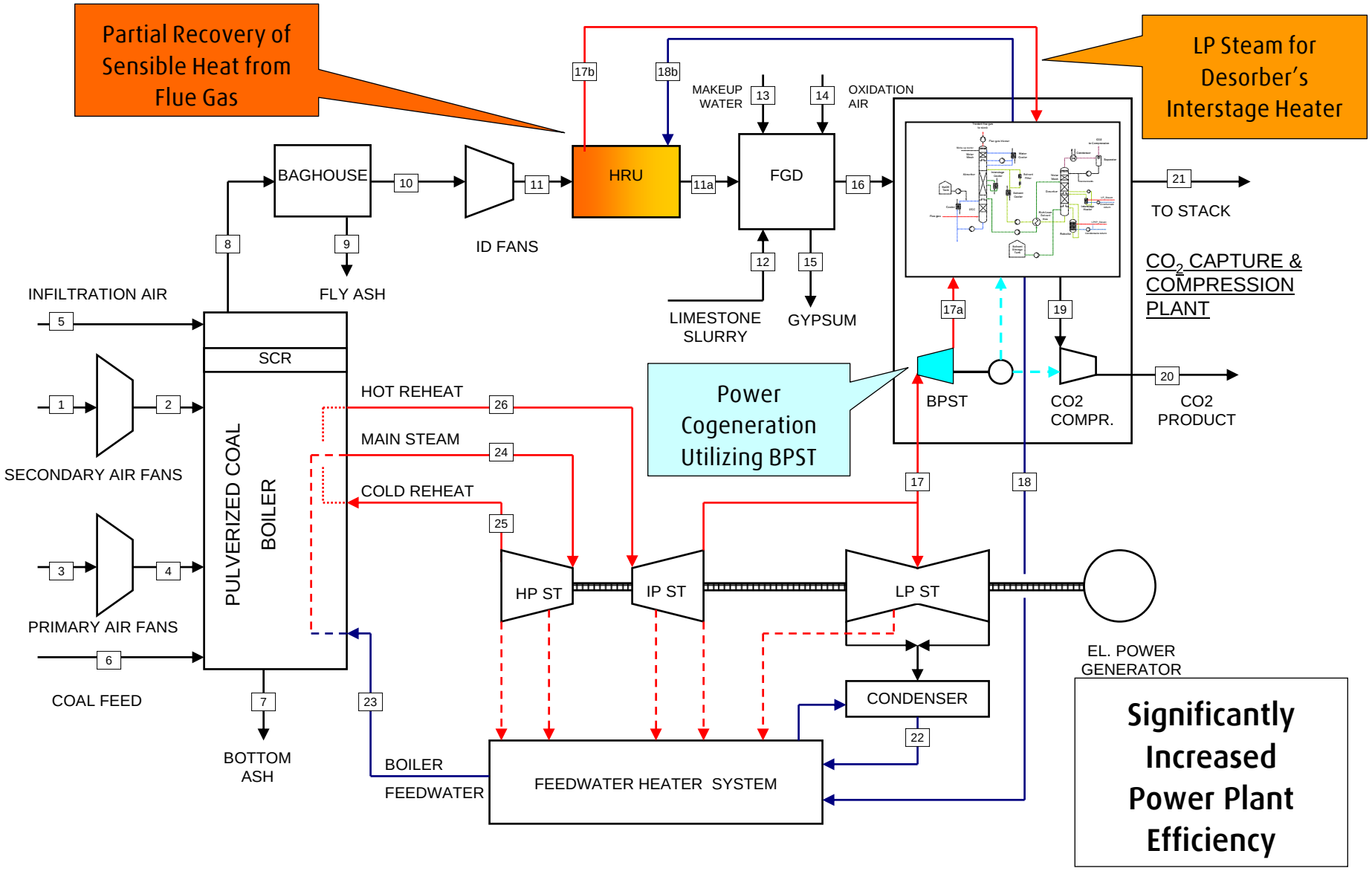
- Brian Research & Engineering ProMax® software for PCC parametric optimization
- BASF's proprietary package for rigorous solvent performance predictions



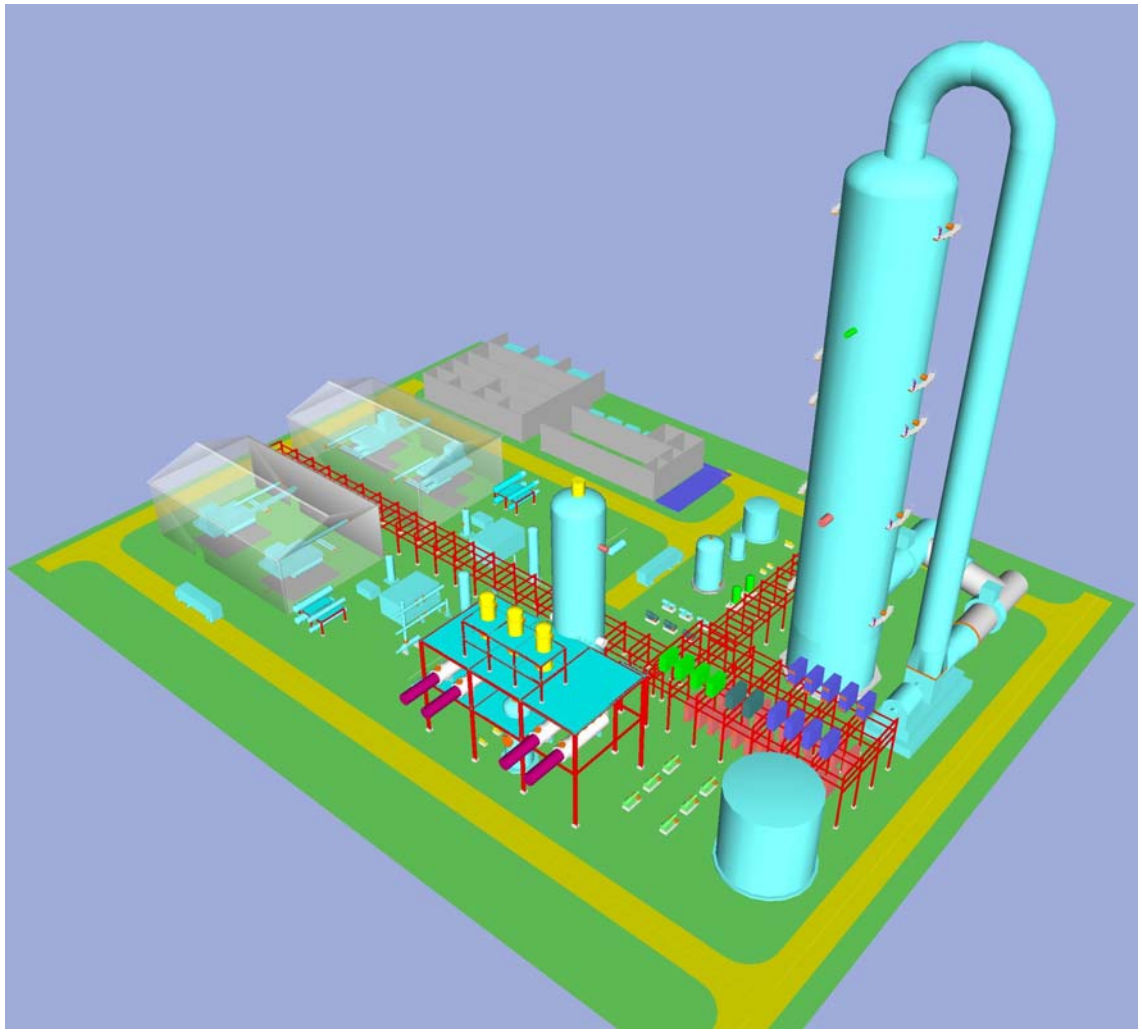
# PCC – Power Plant
# Typical Process Integration Option (LB-1)



# PCC – Power Plant
# Advanced Process Integration Option (LB-2)

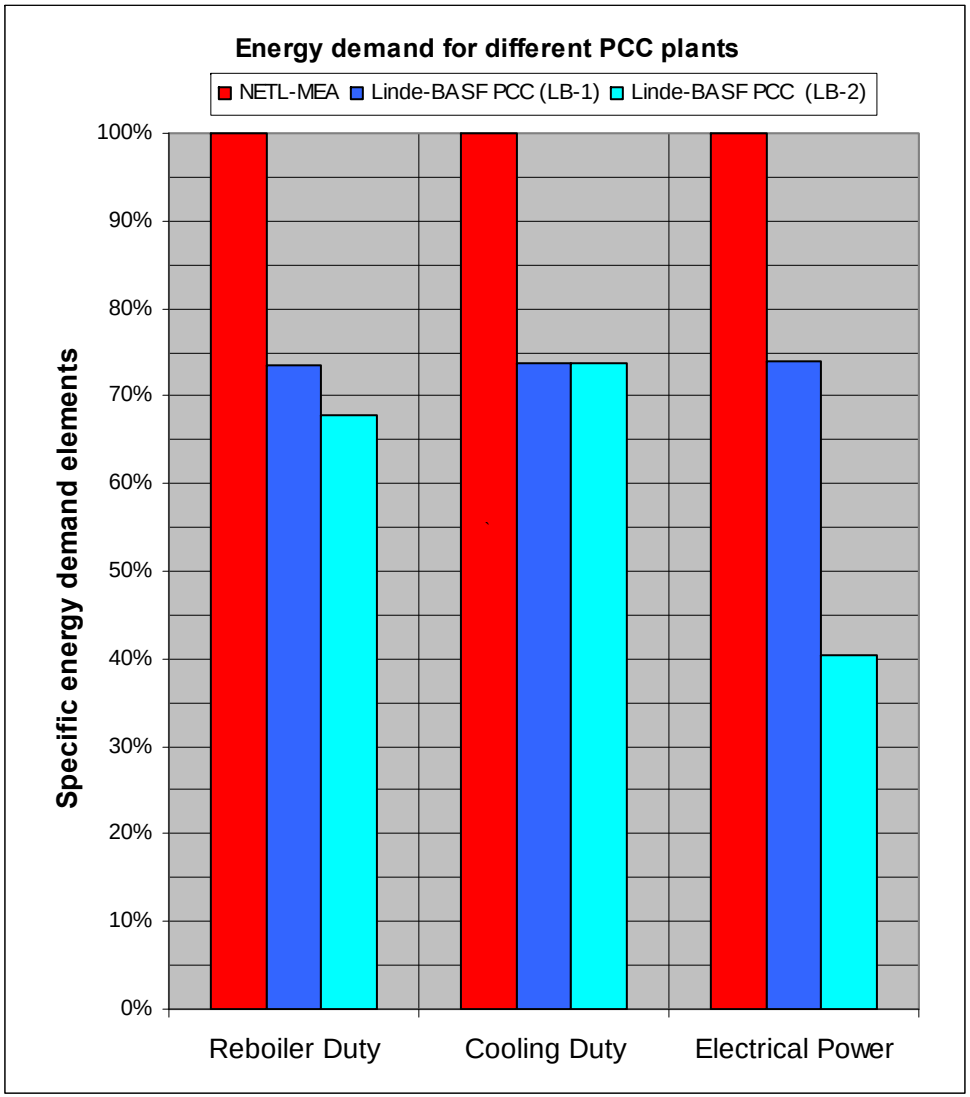


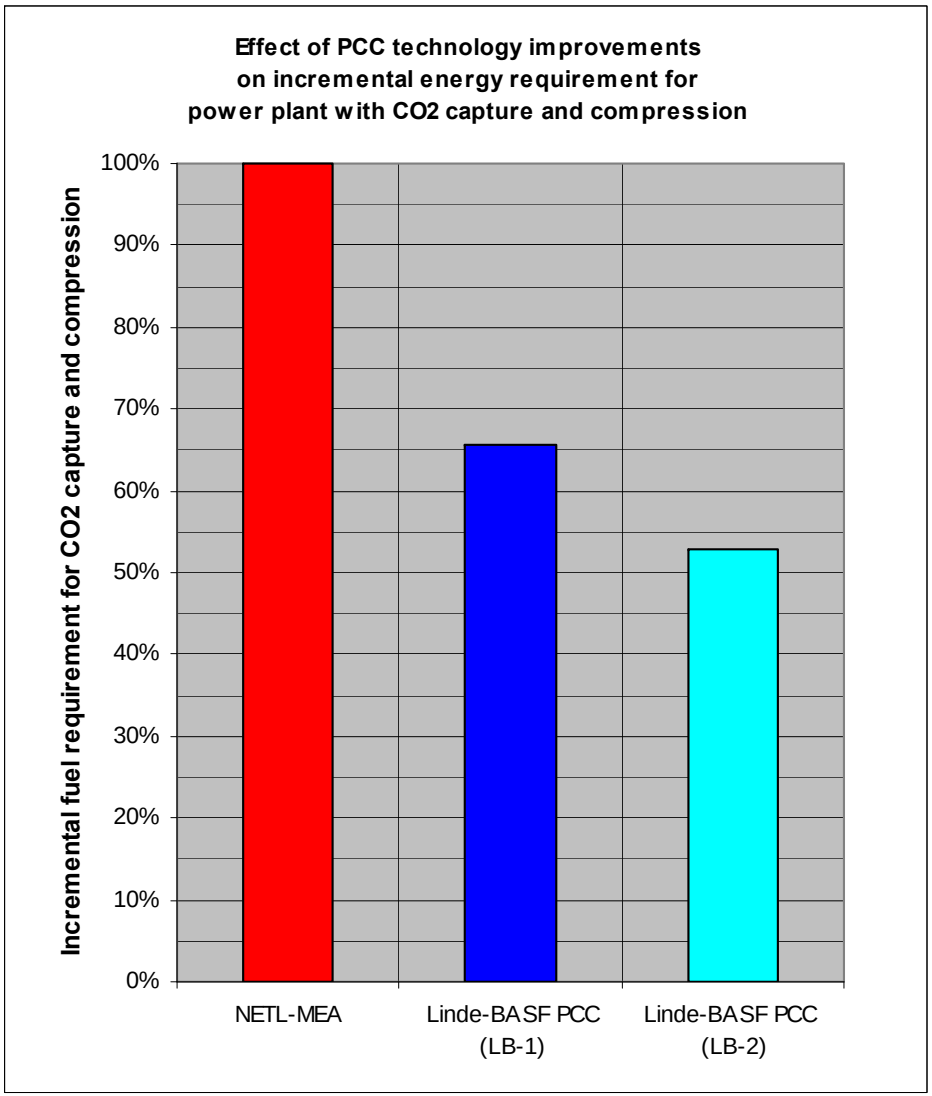
# Linde-BASF PCC Plant Design for 550 MWe PC Power Plant



- 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*

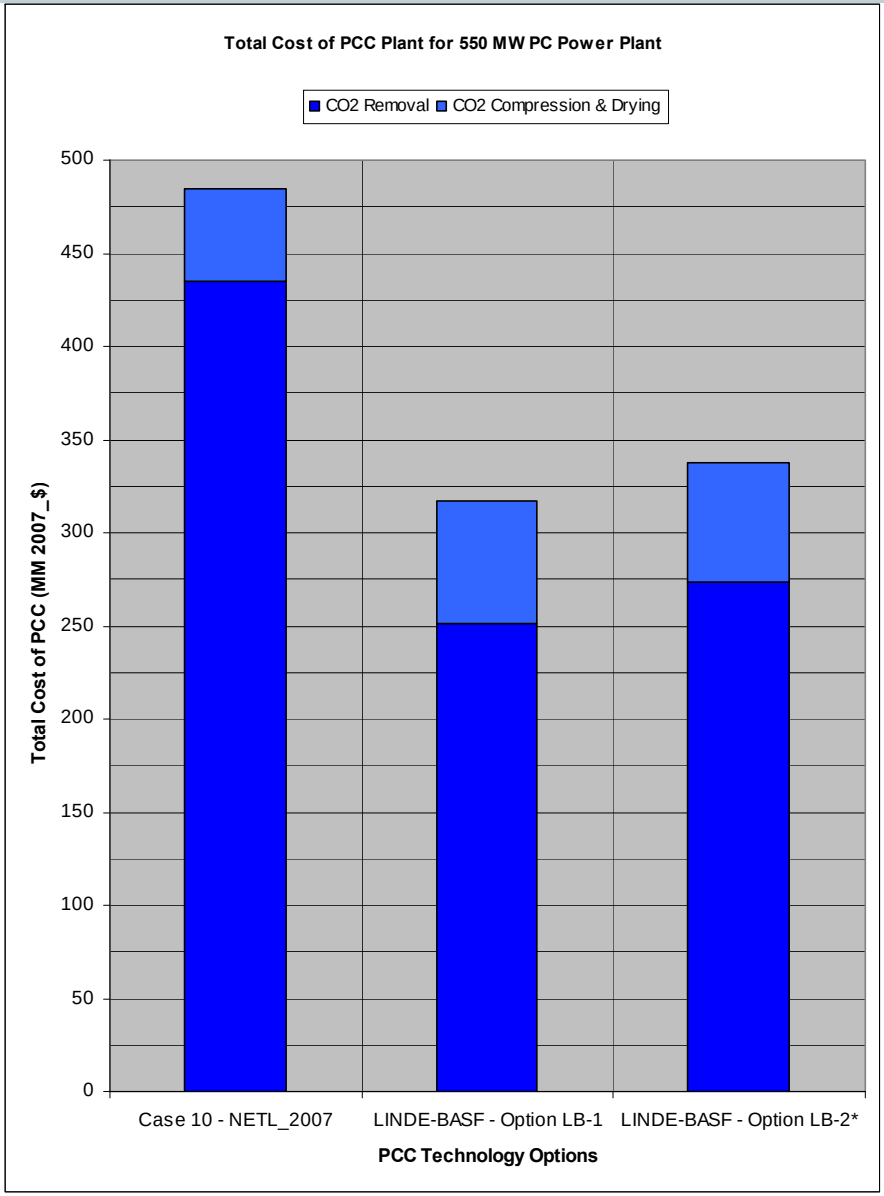





* Reference Case # 10 of DOE-NETL 2007/1281 Report

# Total PCC Plant Cost



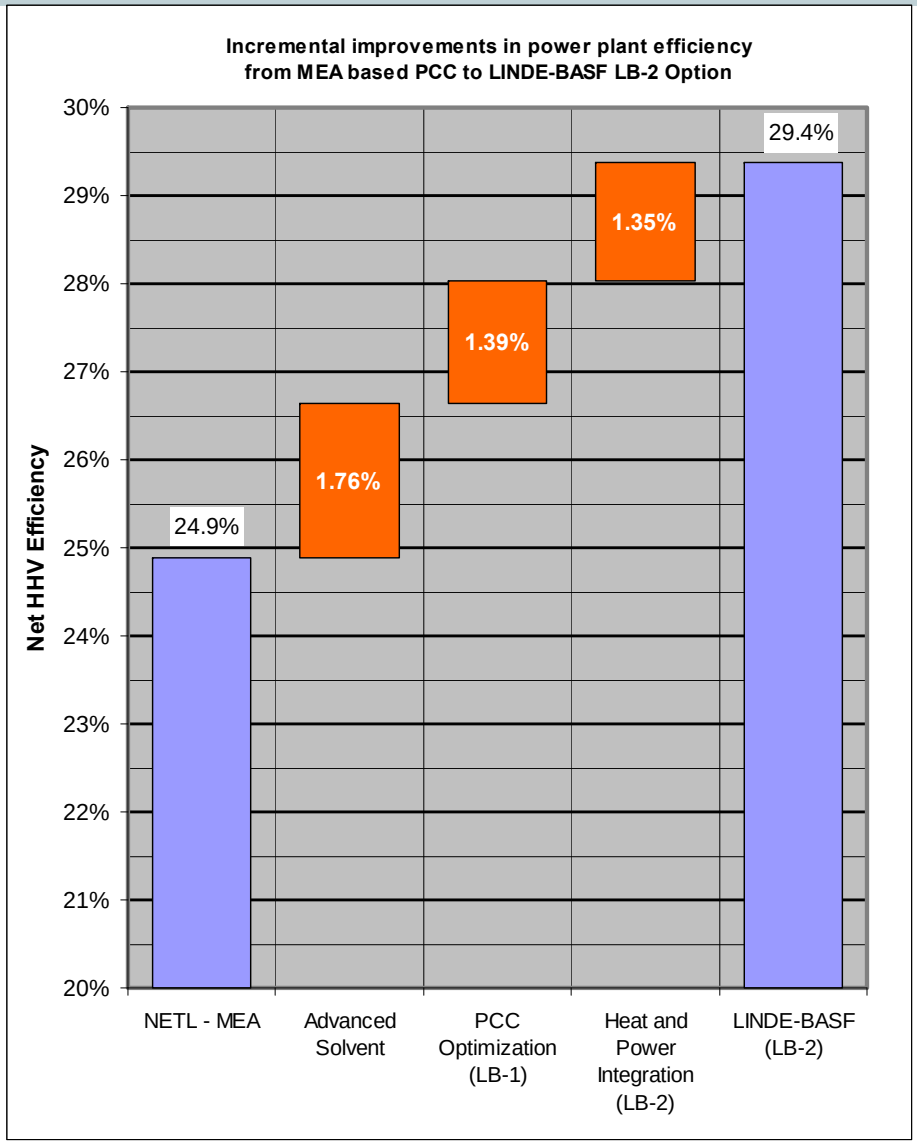

Significantly reduced total PCC plant Cost relative to DOE/NETL 2007 Reference Case #10 due to

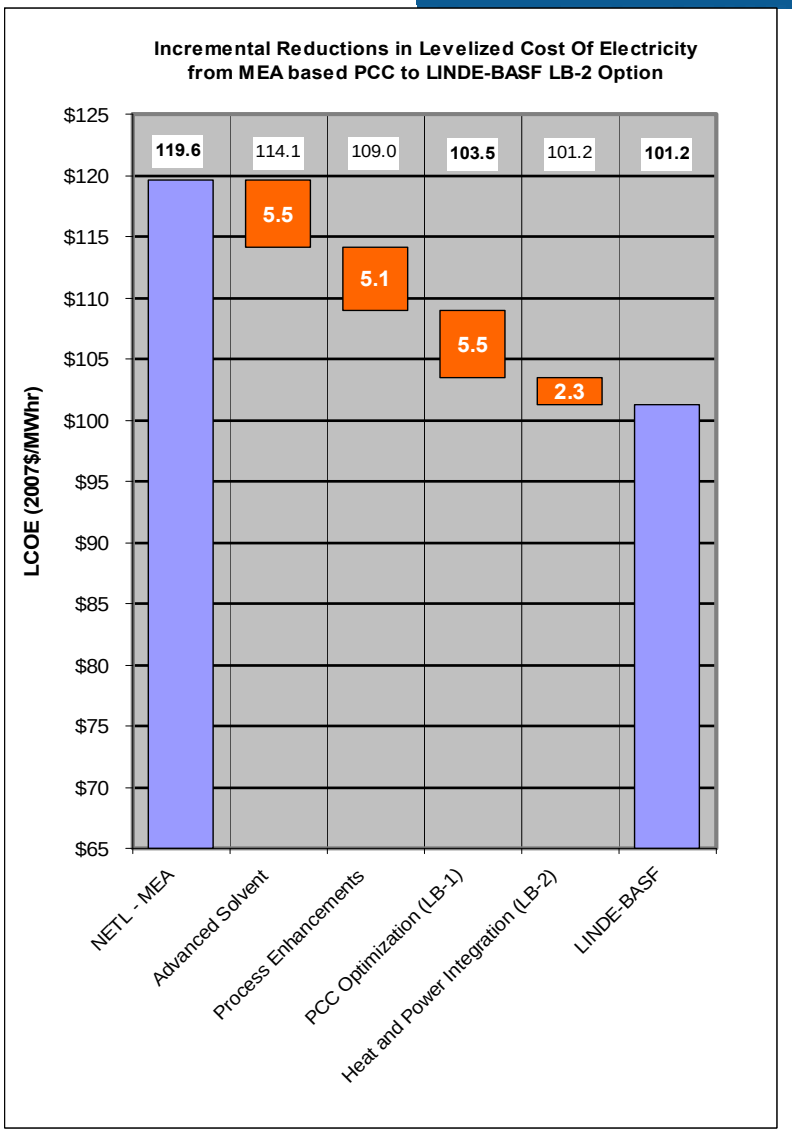
1. Reduced coal combustion (CO2 production) for 11.1% (LB-1) or 15.2% (LB-2)

2. Single train PCC design

3. Optimized PCC plant design

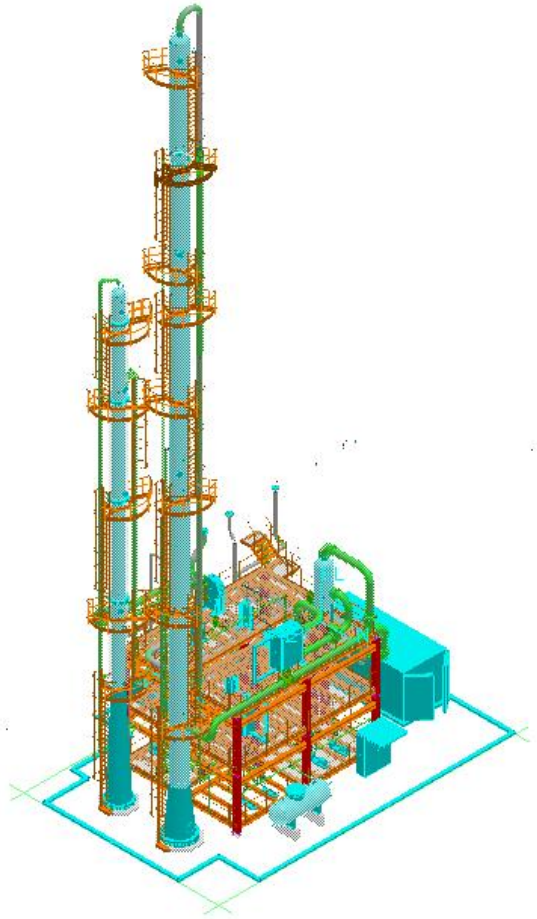
# Power plant efficiency improvements and LCOE reductions with Linde-BASF PCC technology

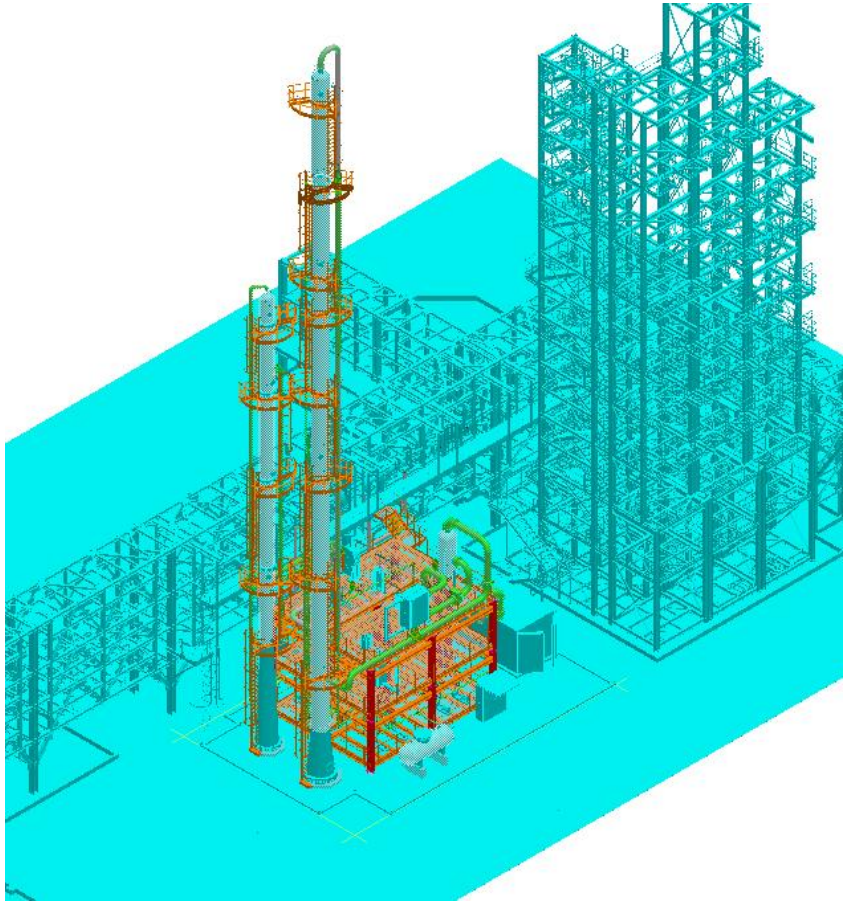



Source: Project DE-FE0007453 Techno-economic analysis of 550 MWe PC power plant with CO2 capture, May 2012.

# 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 exisiting 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.

# Thank you for your attention!

Project DE-FE0007453
2012 NETL $CO_2$ Capture Technology Meeting
Krish R. Krishnamurthy, Linde LLC
July 9-12, 2012
Pittsburgh, PA