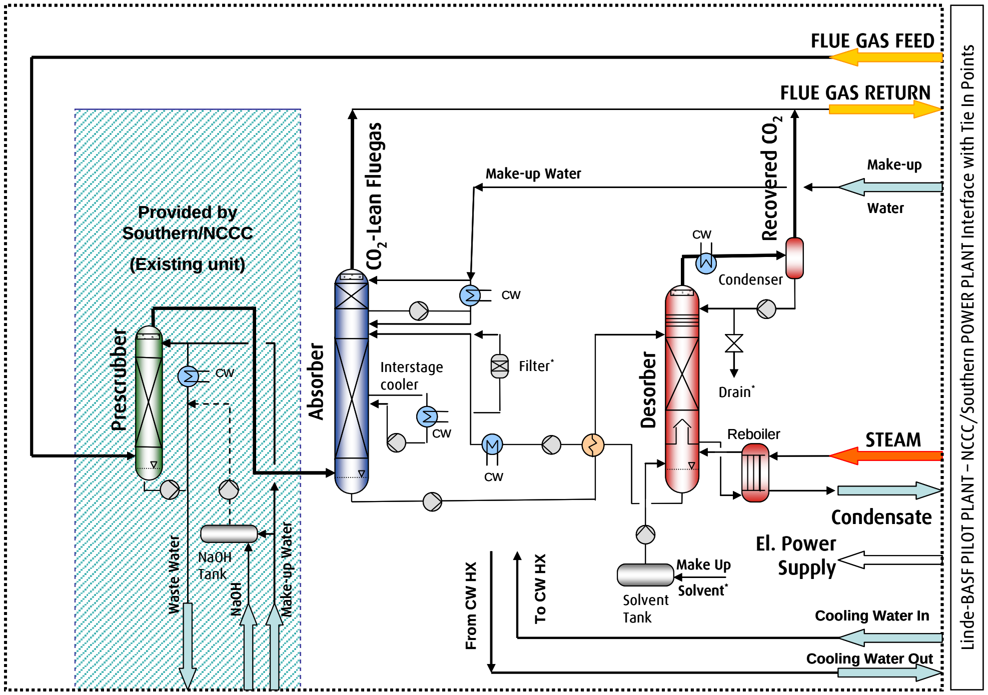
Slipstream pilot plant demo of a amine-based post-combustion capture technology for CO_2 capture from coal-fired power plant flue gas

DOE funding award DE-FE0007453

Project Kick-off Meeting
DOE-NETL, Pittsburgh, PA
November 15, 2011

THE LINDE GROUP

Project Fact Sheet



Scaled-up slipstream Pilot PCC Technology Demonstration

— Selected by DOE for funding

— Contract sign-off in Nov. 2011

— Pilot plant incorporates BASF's novel amine based solvent technology and BASF & Linde process enhancements

Project essentials

— Location: 880 MWel Gaston Power plant (operated by Southern Co.) in Wilsonville, AL

— Site of the National Carbon Capture Center

— Capacity: Up to 6250 Nm^3/h flue gas from coal fired power plant (30 t/d CO_2)

— CO_2 purity 99+ vol % (Dry basis)

— Project start: November 2011

—Project Duration: 4 years

— Partners: Linde LLC, Selas Fluid Processing Corp., Linde Engineering Dresden, BASF, DOE-NETL, EPRI, Southern Company (Host site)

— Project Cost: \$18.8 million

— DOE funding: \$15 million

Project Objectives

THE LINDE GROUP

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

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

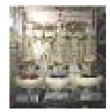
	NG/LNG	Flue gas
Pressure	50 – 100 bars	1 bara
CO_2 partial pressure	1 – 40 bars	30 – 150 mbars
Flowrate	up to 60 mio scf/hr	up to 120 mio scf/hr
Gas composition	CH_4, C_2H_6, …, CO_2, H_2S, COS, C_xH_y,S, H_2O	N_2, O_2, H_2O, CO_2, (SO_x) NO_x
Treated gas specification	50 ppm – 2 % CO_2 S < 4 – 10 ppm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

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

Technology Development Path

Development Path

Laboratory



solvent screening
- screening methods

Mini Plant
0.015 MW_{el}
0.01 mt CO_2 / hr

proof of concept under „synthetic“ conditions
- comparision of solvents
- validate simulation models

Pilot Plant (Niederaussem*)
0.45 MW_{el}
0.3 mt CO_2 / hr

litmus test for new process under real conditions

Pilot Plant (Current)
1 - 1.5 MW_{el}
0.8 - 1.2 mt CO_2 / hr

Advanced design and new materials aimed at emissions reduction and capex reduction in the large scale

Demo Plant
50 - 250 MMW_{el}
34 - 170 mt CO_2 / hr

test of complete CCS-chain
capture, compression, transport, storage/EOR

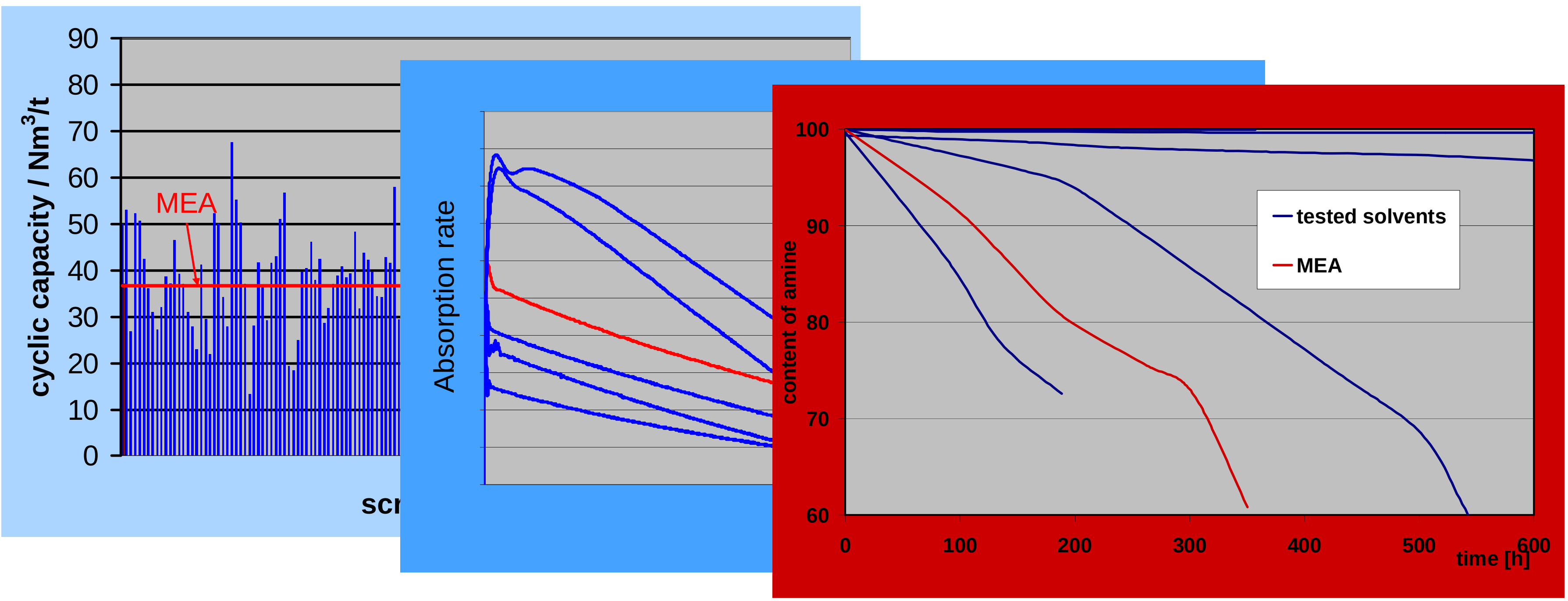
Commercial Plant
500 - 1100 MW_{el}
340 - 750 mt CO_2 / hr

Safe, reliable, and economical operation in compliance with regional and national regulations

Acknowledgement: * Partner and power plant owner/operator: RWE

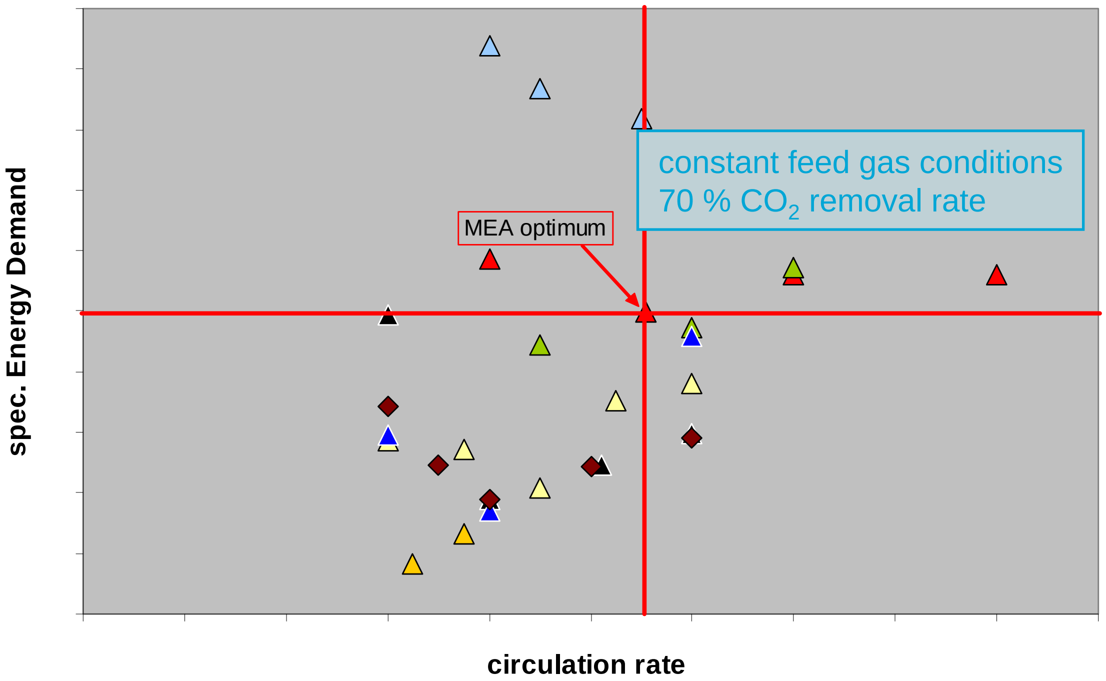
Wide range of solvents screened

Phase Equilibria → **Kinetics** → **Losses/Stability**



BASF Gas Treatment Group

Mini plant – BASF site in Ludwigshafen

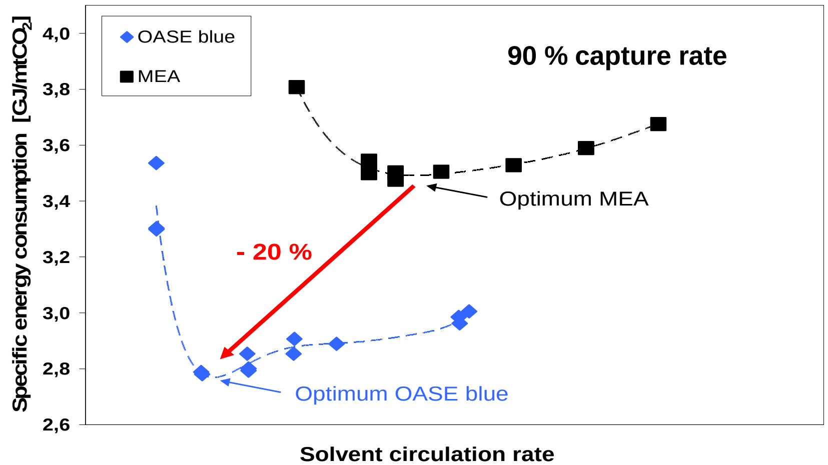


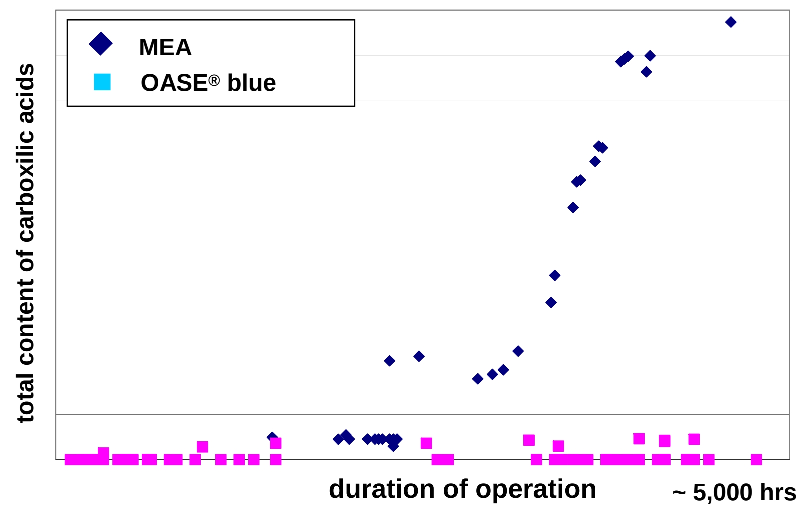
Verification of the screening results

Identification of options for an improved solvent

Niederaussem* pilot plant key results

Acknowledgement: * Pilot project partner RWE





>90% carbon capture rate achieved

>20% improvement in specific energy compared to MEA

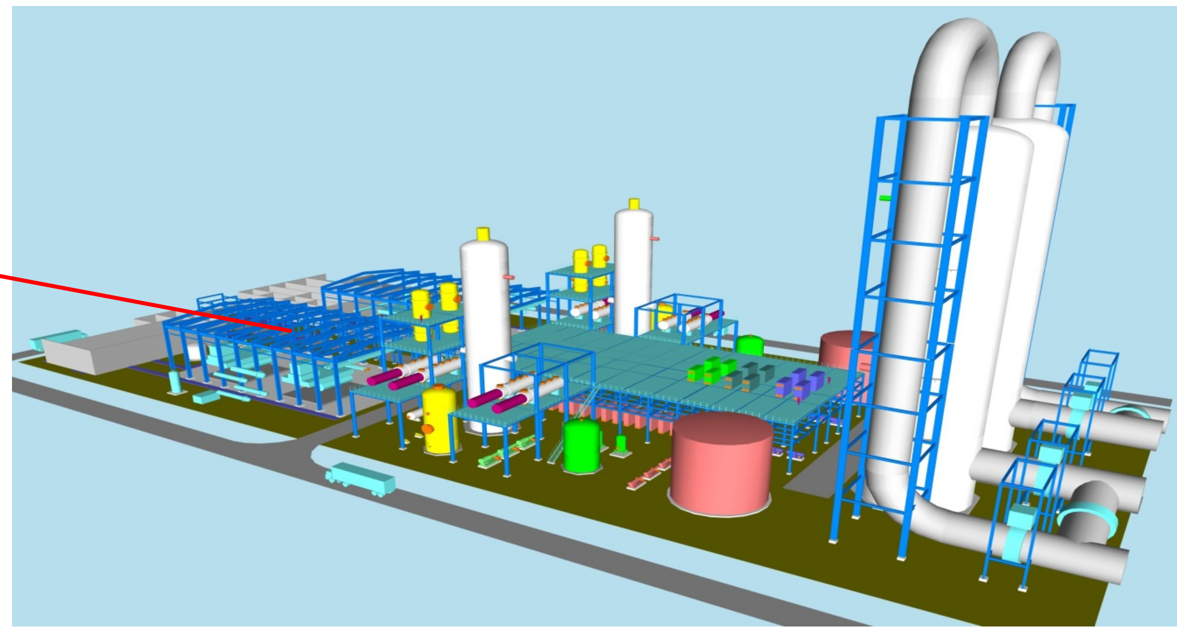
New BASF solvent is very stable compared to MEA

Solutions for Large Scale PCC Plant (1100 Mw_{el} Power) Design challenges

Optimizing CAPEX by reduced number of trains

- 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

THE LINDE GROUP

Linde

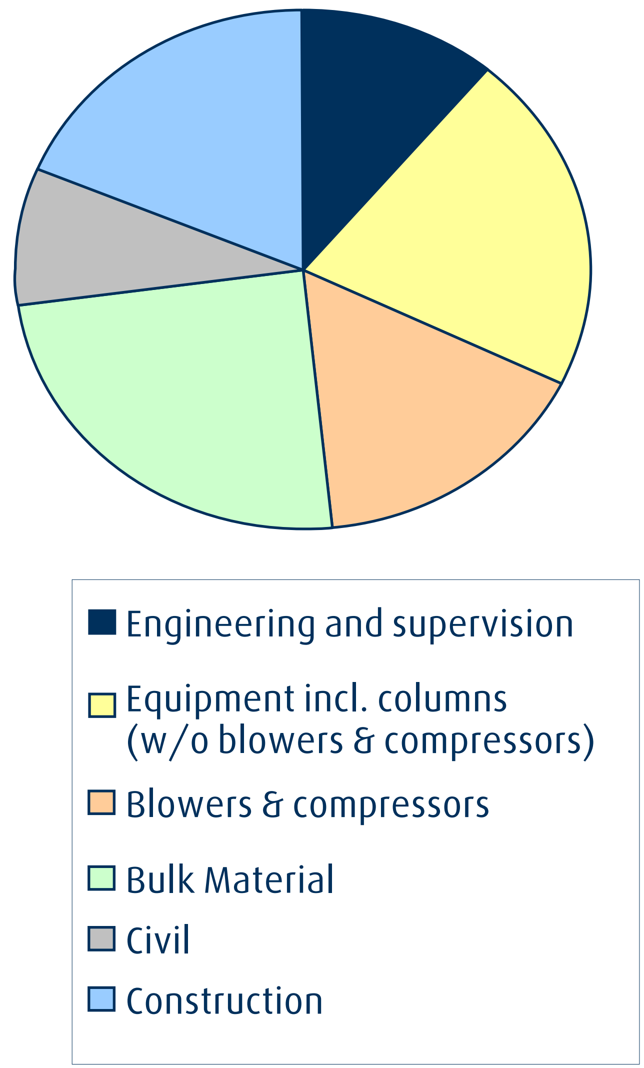
Main challenges

- Large equipment size requires new concepts
- Required plot area is very significant
- Alternative materials needs 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



Project Budget

Source	Budget Period 1 Nov 2011 – Jan 2013	Budget Period 2 Feb 2013 – Jan 2014	Budget Period 3 Feb 2014 – Oct 2015	Total
DOE Funding	$2,287,575	$9,858,828	$2,853,597	$15,000,000
Cost Share	$571,894	$2,464,707	$766,259	$3,802,860
Total Project	$2,859,468	$12,323,536	$3,619,856	$18,802,860

Cost share commitments:

Linde: $3,212,121

BASF: $493,360

EPRI: $97,379

Project Timeline

Task #	TITLE		2012				2013				2014				2015			
		Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1	Program Management	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
Budget Period 1																		
2	Techno-Economic Evaluation	■																
3	Pilot plant optimization and basic design	■	■															
4	Pilot plant system design and engineering		■	■	■													
5	Pilot plant cost and safety analysis			■	■	■												
	Go - No Go DECISION					◆												
Budget Period 2																		
6	Supply of plant equipment and materials						■	■										
7	Plant construction and commissioning							■	■	■								
	Mechanical completion of pilot plant									◆								
Budget Period 3																		
8	Start-up and initial operation										■							
9	Parametric testing											■	■					
10	Long duration continuous operation													■	■	■		
11	Final economic analysis and commercialization plan																■	
	Project Closeout																◆	

Key Project Milestones

THE LINDE GROUP

Linde

- **Budget Period 1 (Nov. 1, 2011 – Jan. 31, 2013)**
  - Project kick-off meeting with DOE-NETL (11/15/2011)
  - **550 MWel power plant with integrated carbon capture techno-economics report (Dec. 31, 2011)**
  - Optimal design parameters identified and pilot plant design completed (April 30, 2012)
  - Host site agreement (Sep. 30, 2012)
  - Pilot plant engineering and equipment sizing complete for cost assessment (Oct. 31, 2012)
  - Development and submission of bid packages (Nov. 30, 2012)
  - **Completed pilot plant costs based on vendor quotes (Dec. 31, 2012)**
- **Budget Period 2 (Feb. 1, 2013 – Jan. 31, 2014)**
  - Pilot plant equipment and modules shop fabrication completed (June 30, 2013)
  - Completed ES&H assessment (Dec. 31, 2013)
  - **Mechanical completion of pilot plant and start-up enabled (Jan. 31, 2014)**
- **Budget period 3 (Feb. 1, 2014 – Oct. 31, 2015)**
  - Pilot plant operations validated and ready for testing (April 30, 2014)
  - **Performance validated against targets (Oct. 31, 2014)**
  - **Long term operability and solvent stability demonstrated (July 31, 2015)**
  - **Technology advantages demonstrated/Ready for commercial (Oct. 31, 2015)**

Project Team and Organization

THE LINDE GROUP
Linde

US DOE NETL
Program Manager
Andrew P. Jones

Contract Administrator
C. Nussgruber - Linde LLC

Program Manager:
K. Krishnamurthy, Linde LLC
Partner Lead Contacts:
I. Clausen – BASF
R. Rhudy – EPRI
L. Kogan – SFPC
T. Stoffregen – Linde Eng.
F. Morton – Host Site (NCCC)

Power Plant Advisory Board (TBC)
Santee Cooper
Southern Co.
EPRI

- Task 1 – Program Management
  Linde LLC Lead
- Task 2 – Techno-Economic Evaluation
  Linde LLC Lead
- Task 3 – Pilot Plant Design Optimization and Basic Design
  BASF/Linde Eng. Lead
- Task 4 –Pilot Plant System Design and Engineering
  SFPC Lead
- Task 5 – Pilot Plant Cost and Safety Analysis
  SFPC Lead
- Task 6 – Supply of Plant Equipment
  SFPC Lead
- Task 7 – Plant construction and commissioning
  SFPC Lead
- Task 8 – Start-up and Initial operation
  BASF/Linde Eng. Lead
- Task 9 – Parametric Testing
  Linde LLC Lead
- Task 10 – Long Duration Continuous Operation
  Linde LLC Lead
- Task 11 – Final Economics and Commercialization
  Linde LLC Lead

Success Criteria at Decision Points

THE LINDE GROUP

Linde

Decision Point	Date	Success Criteria
Go – No Go decision to build pilot plant	**12/31/2012**	**1.Techno-economic evaluation completed and accepted by DOE-NETL. It demonstrates benefits of the proposed development. 2.Cost estimates and schedule for the pilot plant meet targets.**
Mechanical completion of pilot plant	**1/31/2014**	**1.Pilot plant construction has been completed. 2.Process and safety checks have been performed successfully and plant ready to start up and operate.**
Project Closeout	**10/31/2015**	**1.Slipstream pilot plant testing and data analysis successfully completed. Results show the benefits of the PCC technology with the novel amine-solvent as predicted or better.**

Risk Management (2)

THE LINDE GROUP
Linde

Description of Risk	Probability (Low, Moderate, High)	Impact (Low, Moderate, High)	Risk Management (Mitigation and Response Strategies)
Management Risks:			
Schedule impact due to conflict with other projects (e.g. MTR membranes) scheduled at the NCCC site	Medium	Medium-High	• Have initiated discussion with various stakeholders • Follow up and find middle ground/options to resolve impact on overall project schedule
Additional project complexity due to unforeseen requirements on safety, environment, etc. or significant cost escalation	Low-Medium	Medium	• Control and simplify scope to focus on key technology validation needs • Go/No Go decision set to address significant cost escalation

Risk Management (1)

THE LINDE GROUP

Linde

Description of Risk	Probability (Low, Moderate, High)	Impact (Low, Moderate, High)	Risk Management (Mitigation and Response Strategies)
Technical Risks:			
Testing of new materials and new process options	Low-Medium	Medium	• Leverage overall team expertise • Leverage external partners know-how
Integration with the other test units operating at NCCC	Low	Medium	• Joint meetings to understand issues and incorporate into design and control logic & operations
Resource Risks:			
Availability of key individuals with past experience and know-how	Medium	Medium	• Commitment from all participant to make project successful

Technical approach to optimize performance and reduce capex and opex for future commercial offering

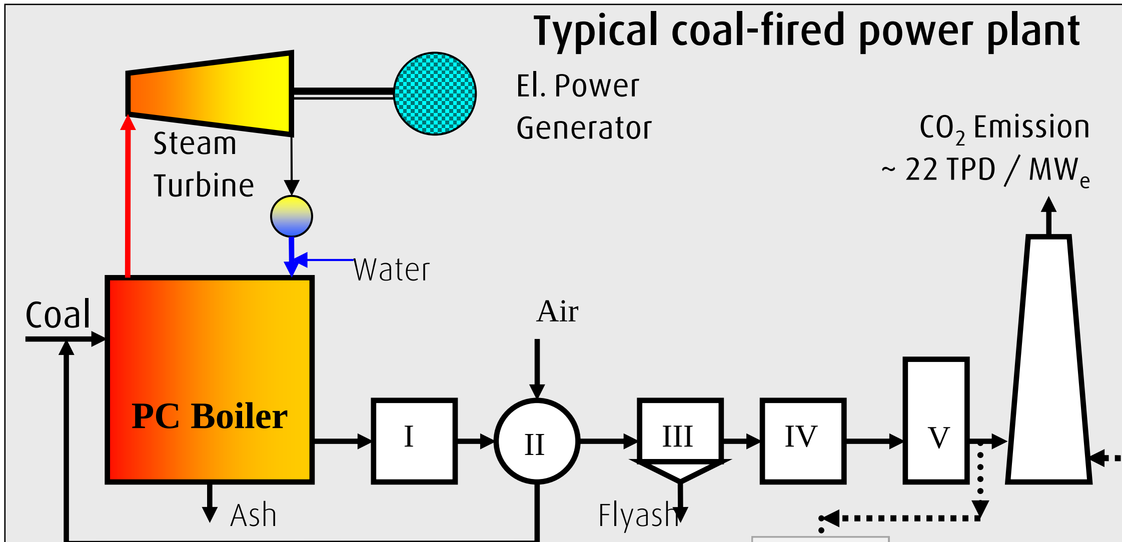
THE LINDE GROUP

Linde

- Select leading solvent (from development till date) for pilot plant design and planned testing. One potential additional solvent to be considered in 2014 when pilot plant in operation.

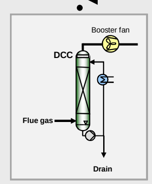
- Process testing and validation for lower capex & opex and for emission reduction:
  - New absorber construction materials (e.g. Concrete columns with in-liner)
  - Advanced absorber structured packing material
  - Absorber intercooling without forced recirculation
  - Optimized equipment arrangement (blower, sump, intercoolers)
  - Advanced stripper design
  - Optimized process parameters to reduce steam consumption (e.g. Regeneration pressure)
  - Reduced emisson losses through optimized wash system

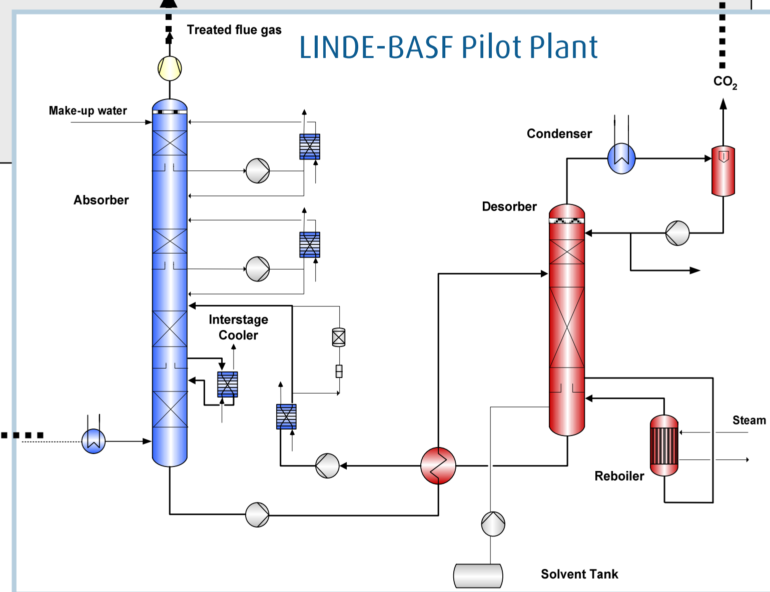
Task 3: Design Selection
Slipstream PCC Pilot Plant: Overall Process Schematic



Host Site: 880MWel Gaston coal fired power plant, Wilsonville, AL (managed by Southern Co.). The facilities are part of the National Carbon Capture Center.

I - NOx Control; II - Air Heater; II - PM Control; IV - Hg Control; V - FGD; VI - Stack

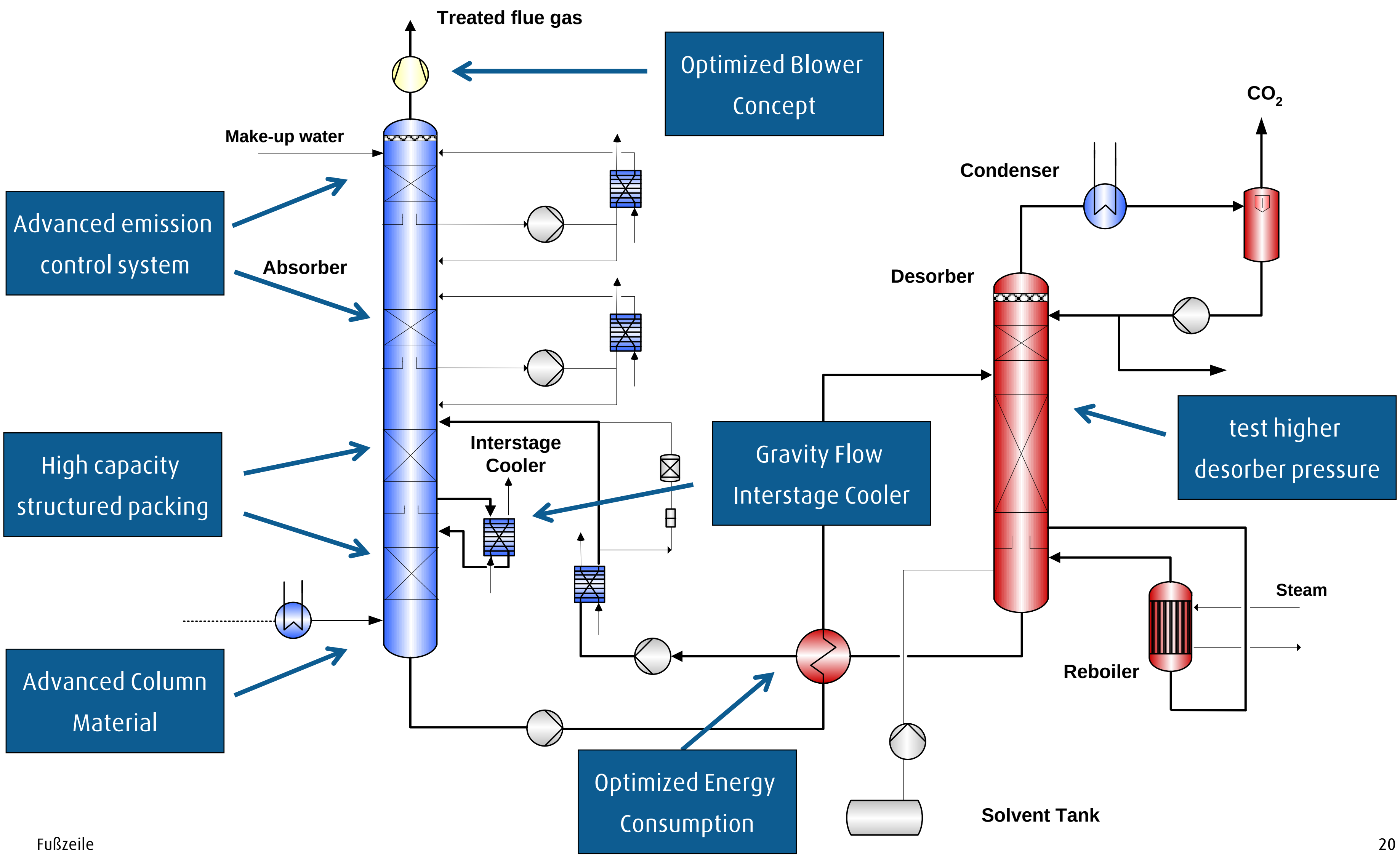




Power plant provides:
steam for PCC regeneration,
cooling water for all HX,
and electrical power.
Accepts flue gas return after CO_2 capture

Task 3: Design Selection
New components to be tested in the pilot plant

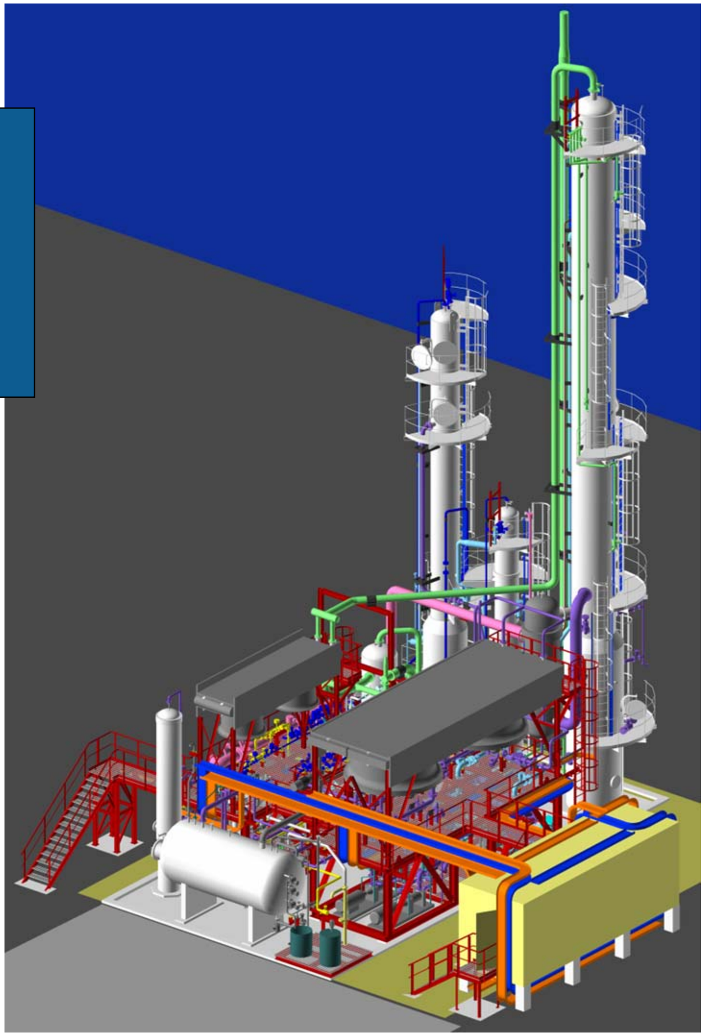
THE LINDE GROUP



Task 3: Design Selection
Pilot Plant Layout

Optimized plant layout

to be investigated



Task 2. Techno-economic assessment
Specifications & Computational platform

THE LINDE GROUP

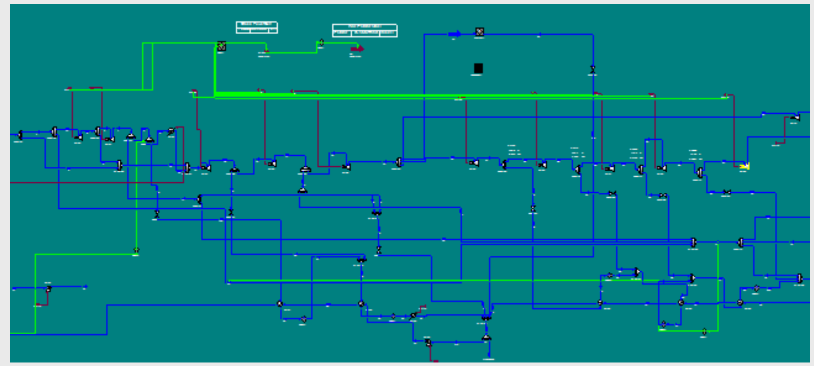
Linde

Specifications and Design Basis

identical to DOE/NETL Report 2007/1281

- Coal Feed Characteristics
- Site Characteristics and Ambient Conditions
- Boiler Design and Steam Turbine Design
- Steam Cycle Conditions
- Environmental Controls and Performance
- Balance of Plant
- Economic Assumptions and Methodology

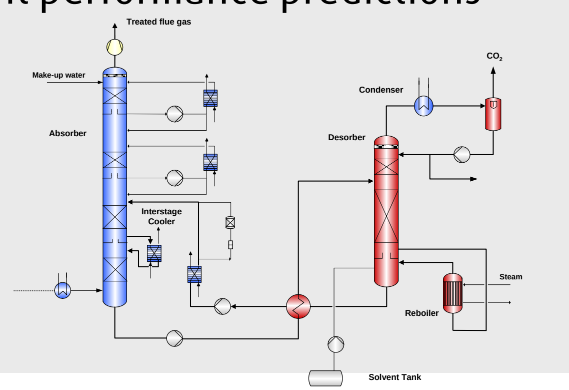
Computational Platform



UniSim Design Suite R390, integrated with

— Linde's custom developed thermodynamic model for Illinois # 6 coal combustion

— BASF's proprietary package for rigorous solvent performance predictions



Task 2. Techno-economic assessment
Approach

THE LINDE GROUP
Linde

Model Calibration

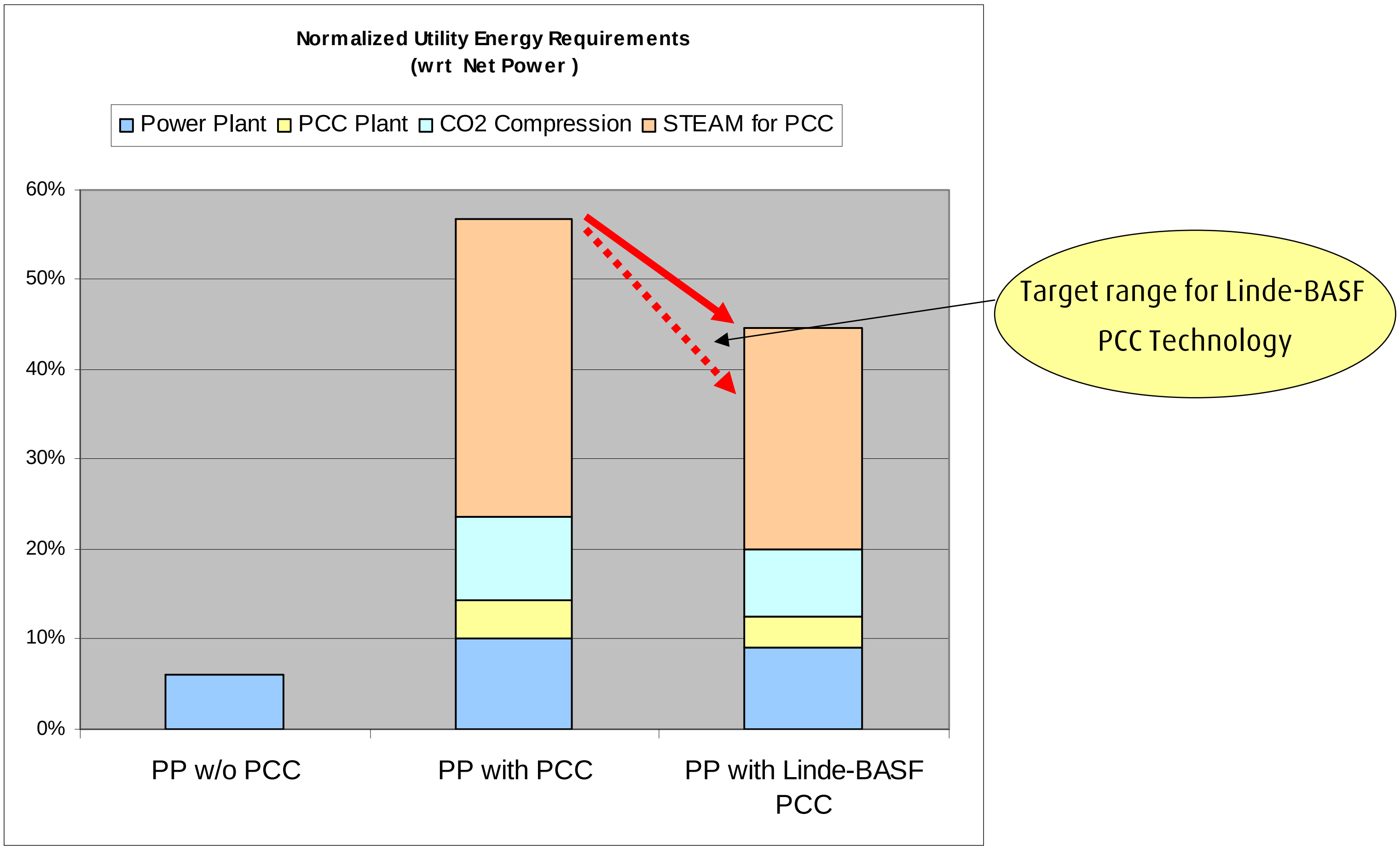
- Match material and energy balances for DOE-NETL Cases # 9 & #10
- Determine adiabatic efficiencies of utilized steam turbines
- Develop reference scale factors for CAPEX assessment at the equipment level
- Verify entire methodology vs reported LCOE values for Cases 9 & 10

Model Application

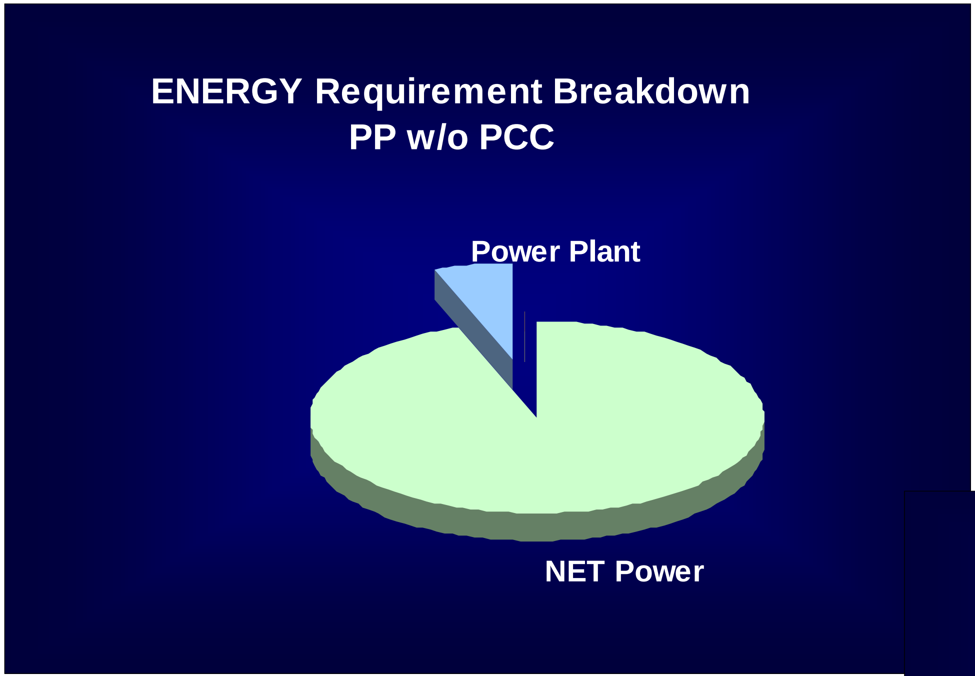
- Modify model for BASF's novel amine based solvent technology and BASF & Linde process enhancements
- Include various process integration and heat recovery options
- Perform sensitivity analyses
- Goal: Minimize LCOE

Task 2. Techno-economic assessment
Energy requirement for PCC

THE LINDE GROUP

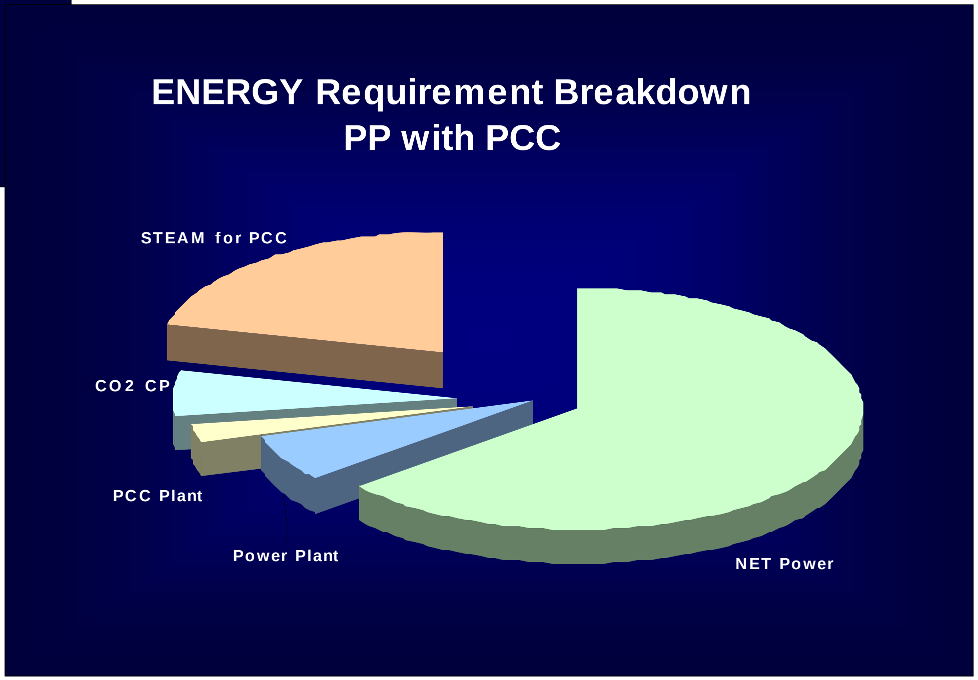


Task 2. Techno-economic assessment
LCOE Dependence on PCC Efficiency

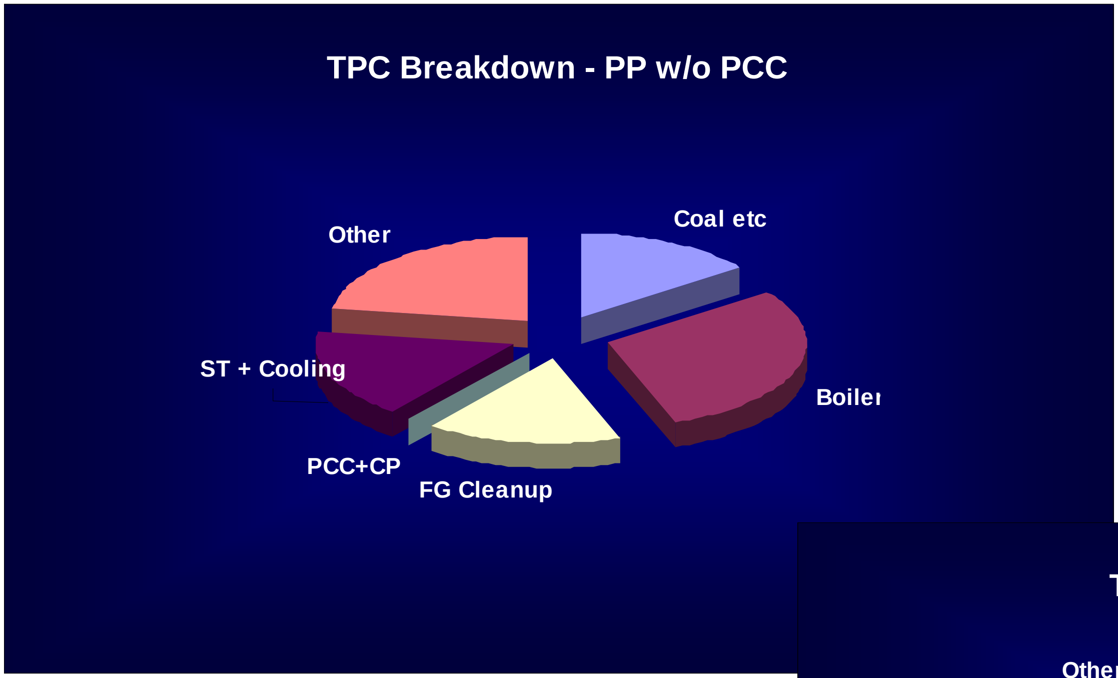


Incremental energy requirement
(DOE Case# 10) for PCC:

~ 50 % of PP w/o PCC (DOE Case# 9)

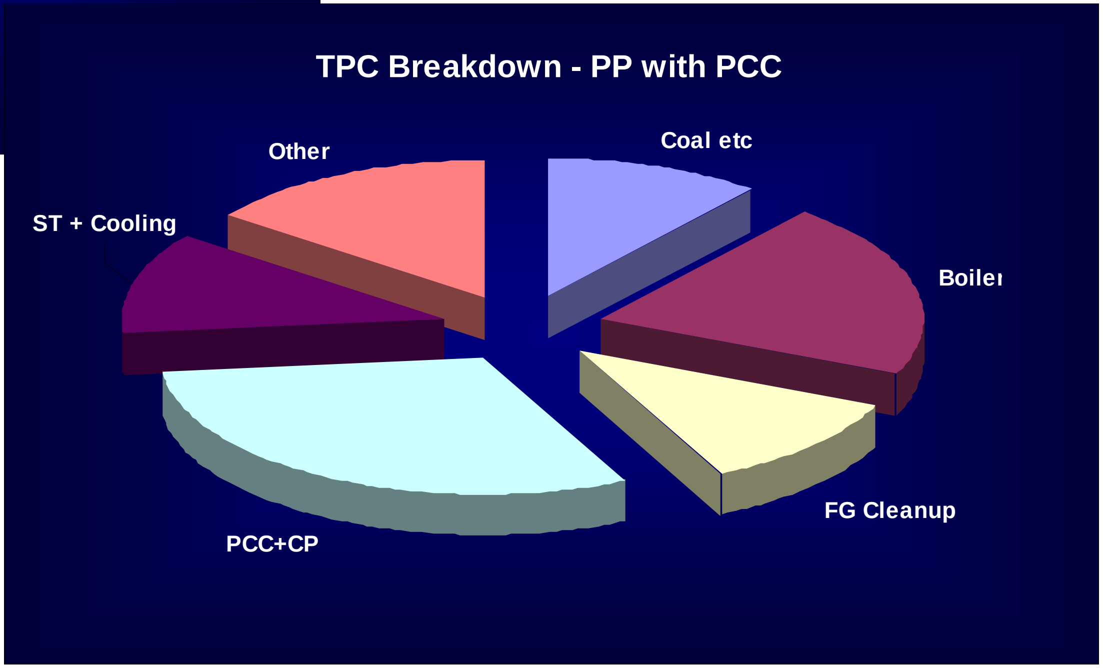


Task 2. Techno-economic assessment
LCOE Dependence on PCC Efficiency

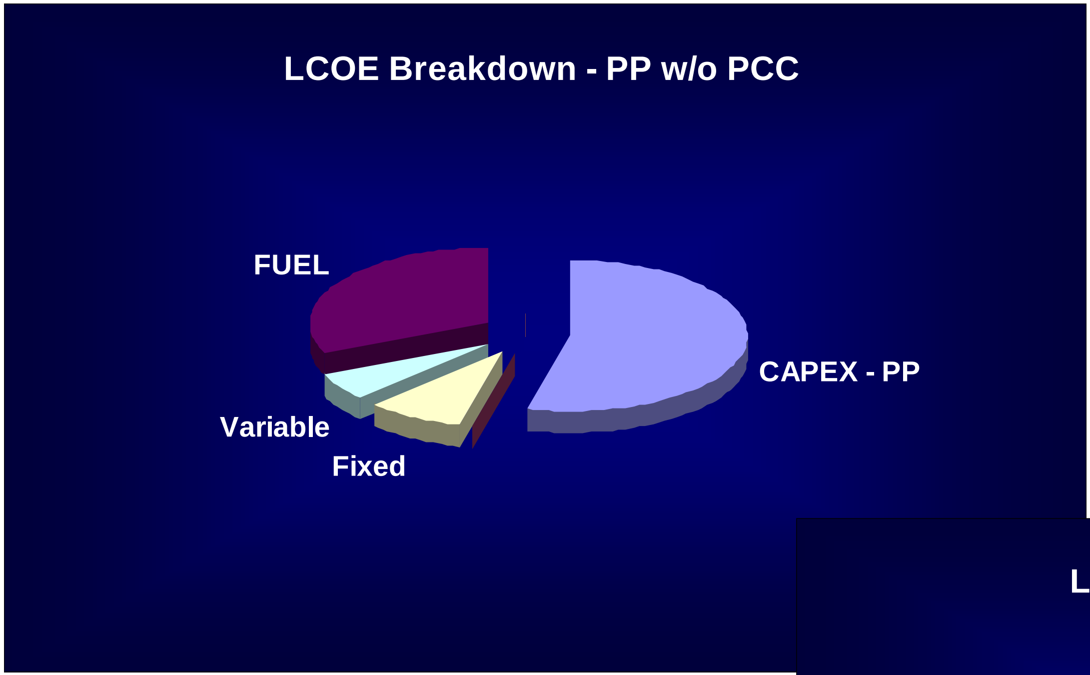


Total Plant Cost of PP with PCC
(DOE Case# 10)

90+% above PP w/o PCC (DOE Case#9)



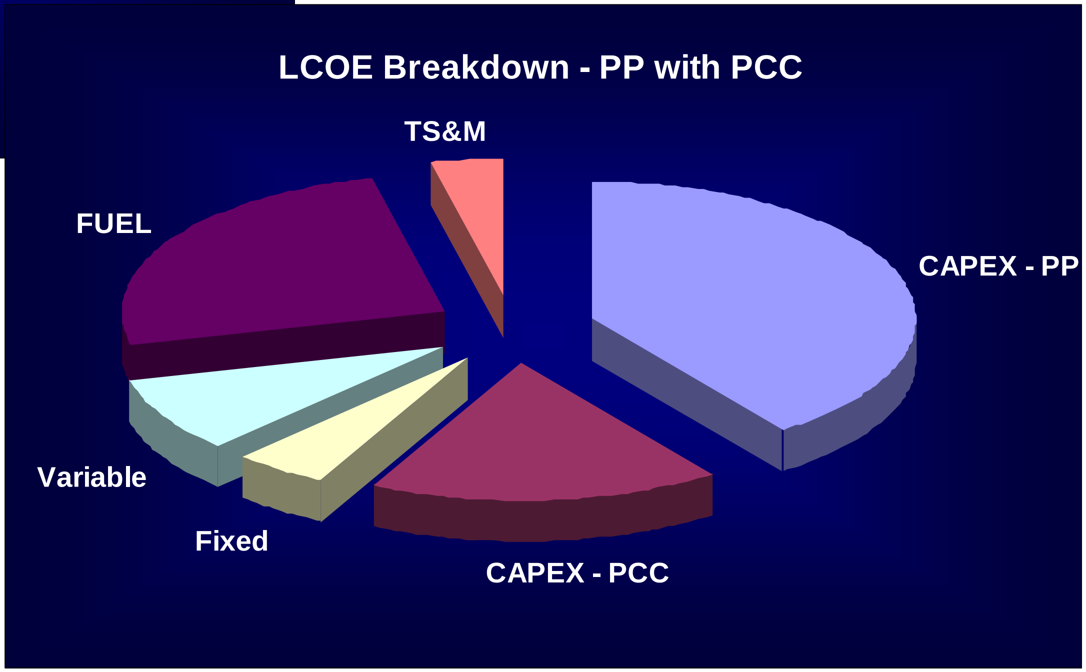
Task 2. Techno-economic assessment
LCOE Dependence on PCC Efficiency



LCOE for PP with PCC (Case#10)

Currently: ~ 86 % above PP w/o PCC (Case#9)

Proposed: < 65 % above PP w/o PCC (Linde-BASF) with options for further reduction



Major targets for LCOE reduction:

— Reduced energy for PCC

— Reduced CAPEX for PCC

— Reduced total energy by process integration and waste heat utilization

Task 2. Techno-economic assessment
Optimization & Status

THE LINDE GROUP

Linde

Techno-economics with Advanced PCC

- BASF's novel amine based solvent technology and BASF & Linde process enhancements
  - Significantly reduced energy requirement
  - Reduced PCC CAPEX and OPEX
- Integration options with Waste heat recovery
  - Within PCC
  - PCC & CO_2 Compression
  - PCC & Power Plant
- Optimization
  - Minimization of LCOE
    - Sensitivity analyses
    - OPEX benefits versus CAPEX cost

Status

- Developed rigorous, integrated Unisim model for 550 MWe power plant with CO_2 capture
- Model integrated with performance parameters of BASF's novel amine based solvent technology
- CAPEX and OPEX reduction options for PCC and CO_2 plants being evaluated
- Rigorous process model being used for sensitivity analyses to highlight key areas for cost improvement
- Various process integration options being analyzed

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!

DE-FE-0007453 Project Kick-off Meeting
DOE-NETL, Pittsburgh, PA
November 15, 2011

THE LINDE GROUP
Linde