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

2013 NETL CO_2 Capture Technology Meeting

Krish R. Krishnamurthy, Linde LLC

July 8-11, 2013

Pittsburgh, PA

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The Linde Group Overview and Carbon Capture Expertise

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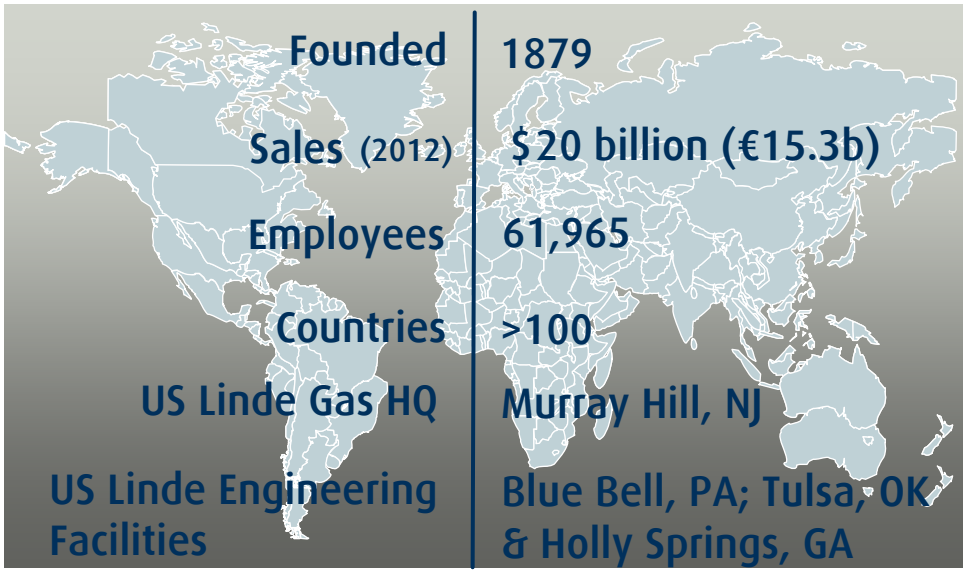
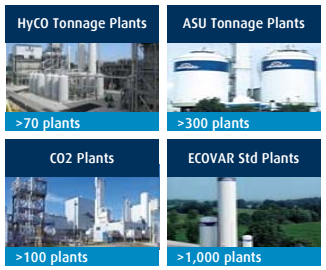


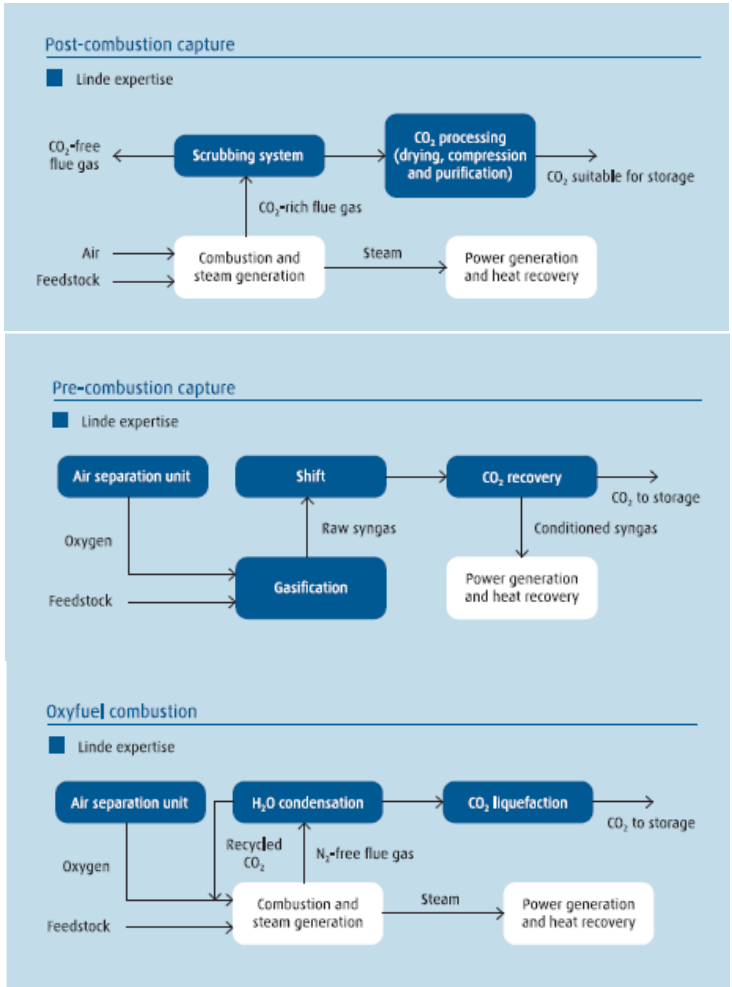
Linde Engineering
Technology-focused

Leveraging Synergies

Linde Gas - Tonnage
World-class operations



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



Project Budget: DOE funding and cost share

Source	Budget Period 1 Dec 2011 – Feb 2013	Budget Period 2 Mar 2013 – May 2014	Budget Period 3 Jun 2014 – Feb 2016	Total
DOE Funding	$2,670,773	$9,367,628	$2,754,564	$14,792,365
Cost Share	$667,943	$2,341,907	$688,641	$3,698,091
Total Project	$3,337,716	$11,709,535	$3,443,205	$18,490,456

Project spend until end of Budget Period 1
$3,240,192

Cost share commitments:

Linde: $3,107,352

BASF: $ 493,360

EPRI: $ 97,379

Project Participants

Partner/ Organization	Lead contact(s)	Key Role(s)
DOE-NETL	Andrew P. Jones, Project Manager	-Funding & Sponsorship
Linde LLC	Krish Krishnamurthy, PI Stevan Jovanovic, Technical Lead	-Prime contract -Overall program management -Operations and testing
BASF	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	-NCCC 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 Engineering North America)	Lazar Kogan Keith Christian	-Detailed engineering -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 Overview: Key Drivers

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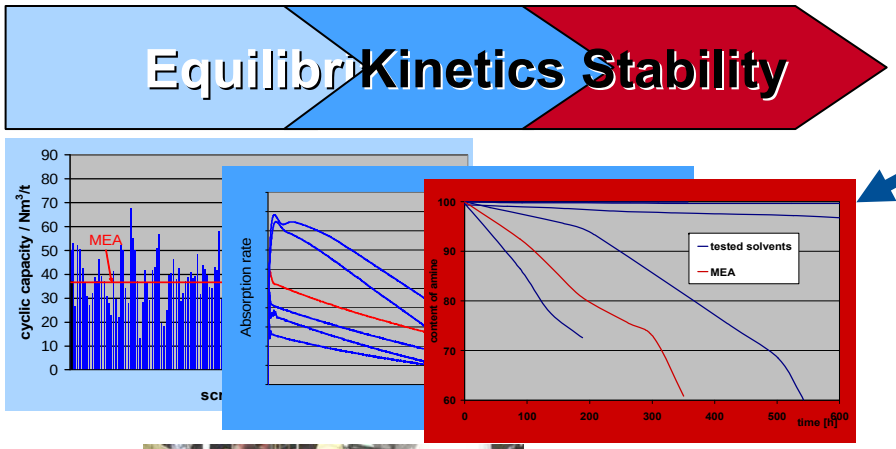
— Post-combustion CO_2 capture technology is flexible and can be applied to both new and existing power plants

— 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)

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

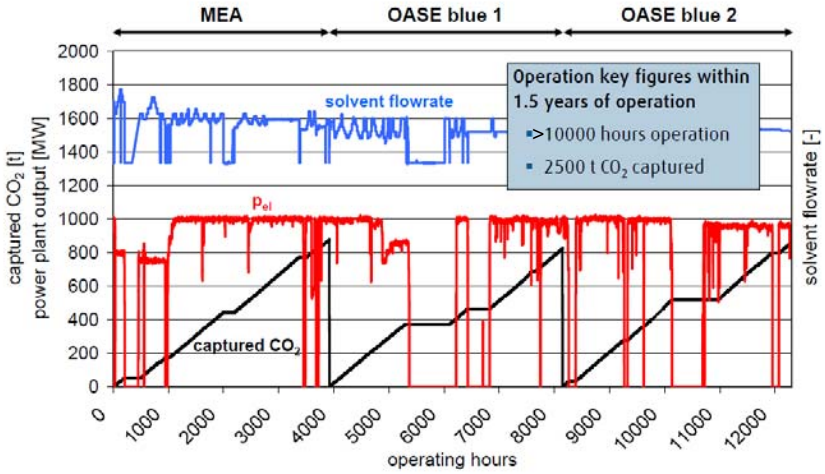
0.45 MWe PCC Pilot, Niederaussem, Germany: Preliminary Process Optimization

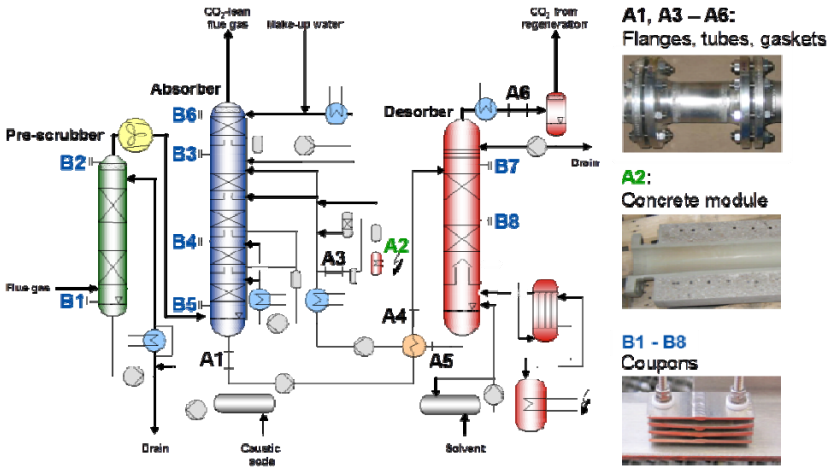
Niederaussem Pilot Plant: Main results of Phase I

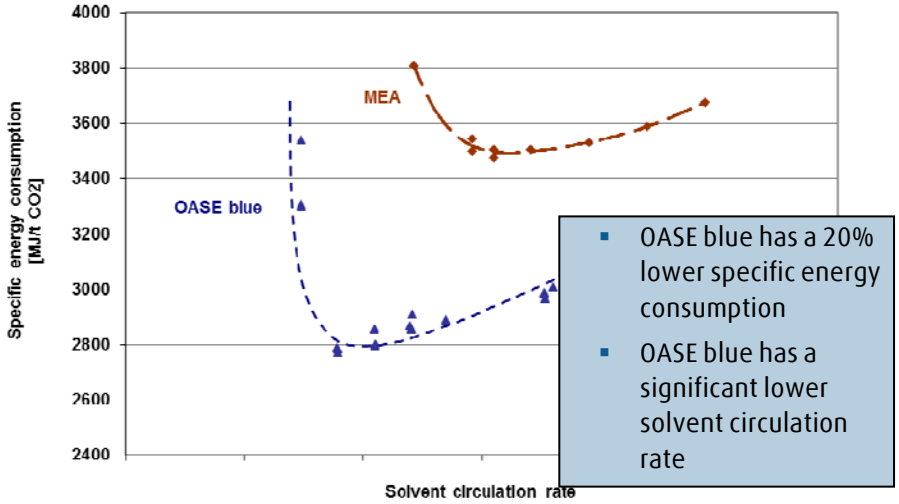
RWE The energy to lead

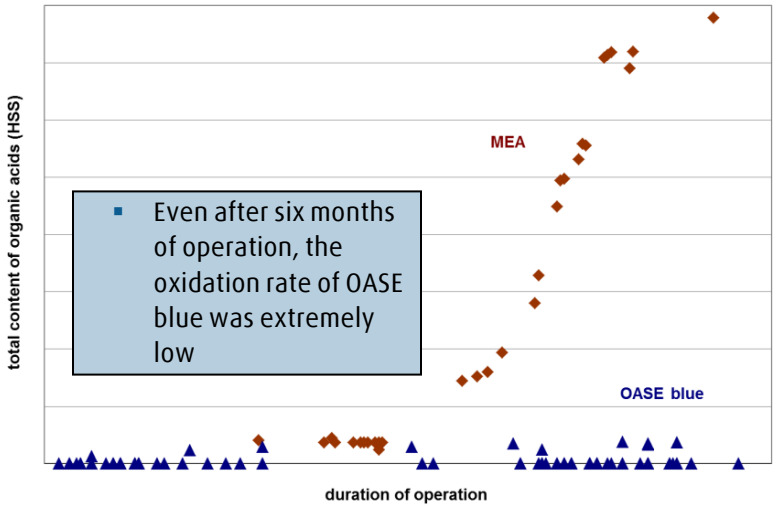
BASF The Chemical Company

THE LINDE GROUP Linde

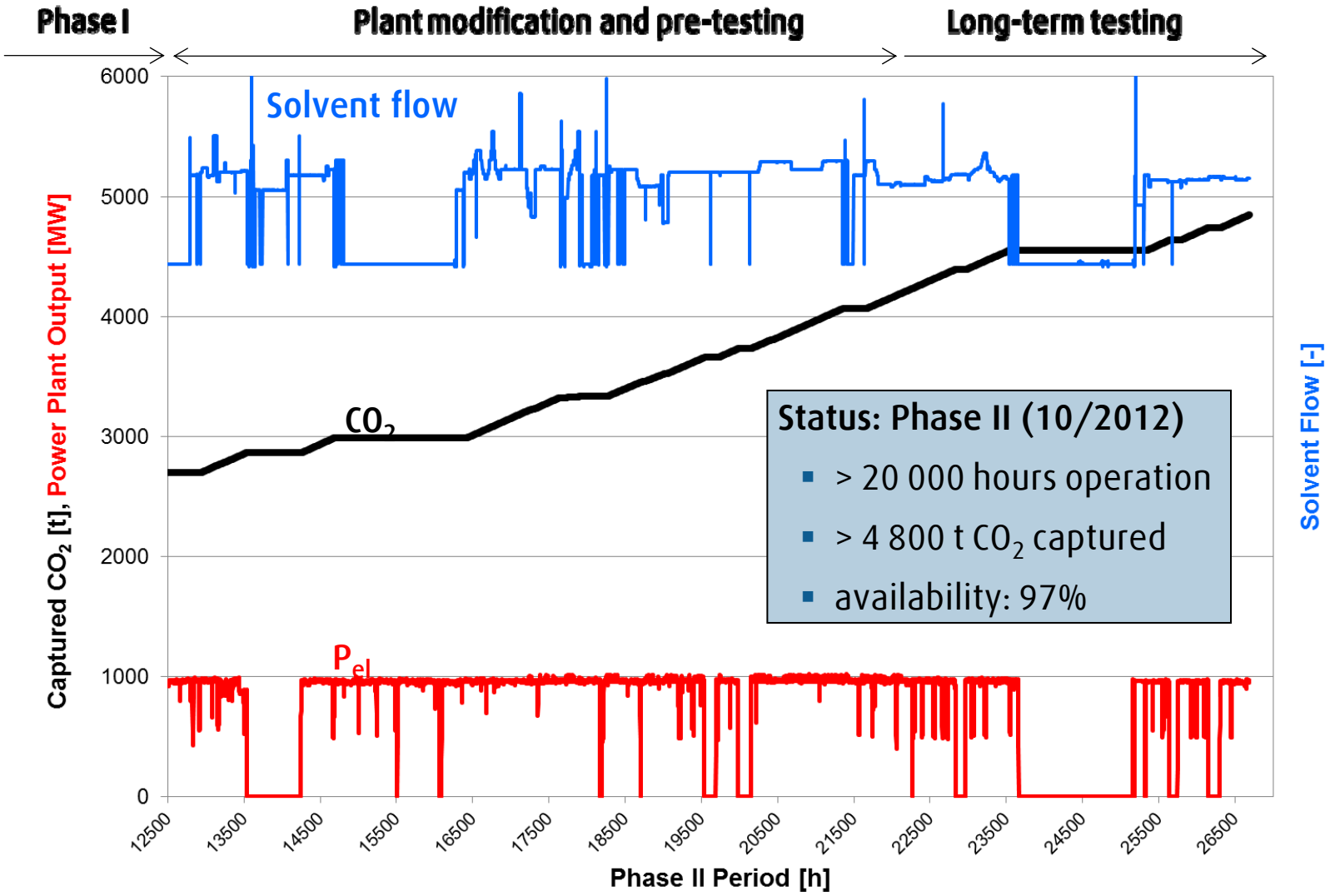




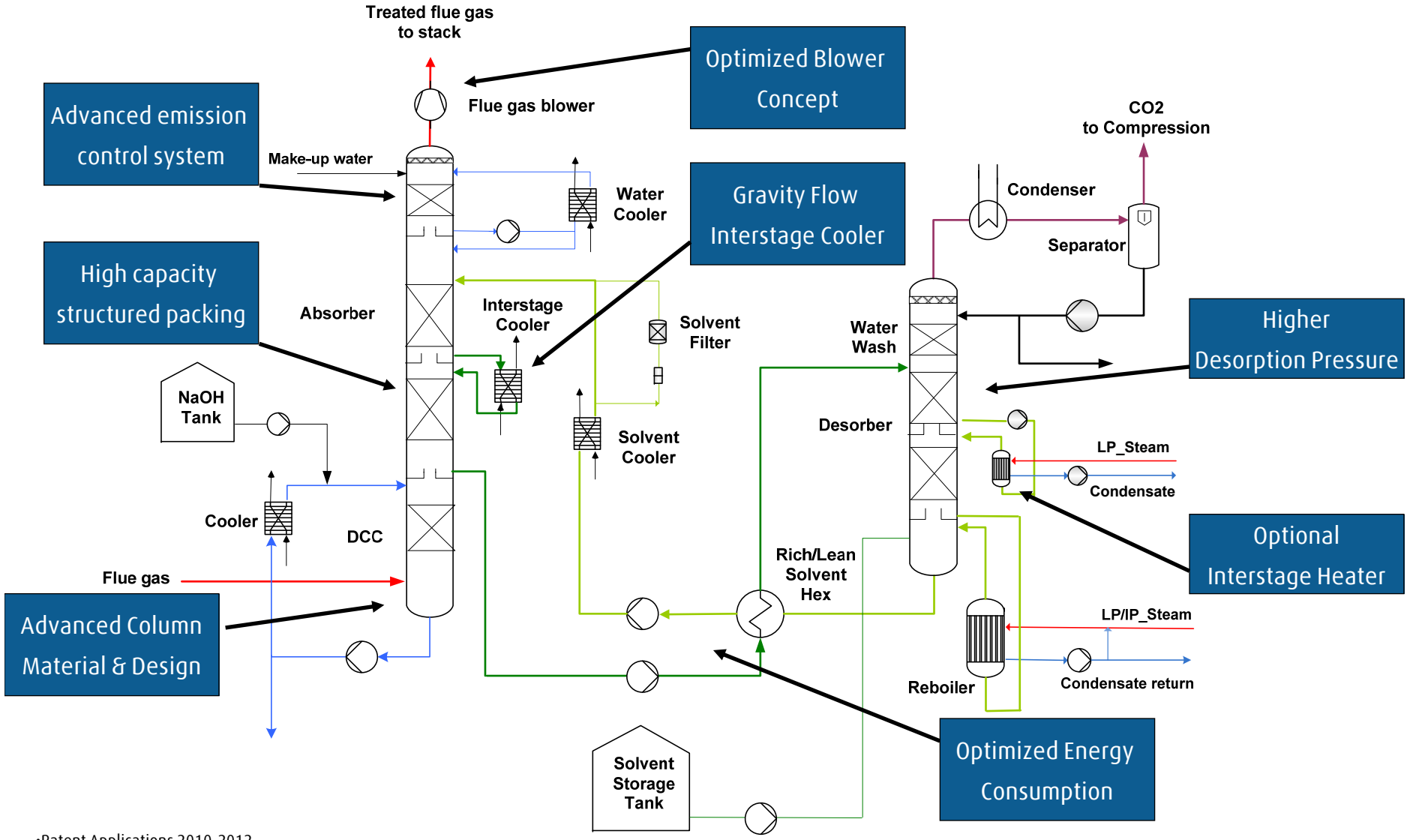




Niederaussem Pilot Phase II: Long term testing evaluating materials, solvent degradation and emissions reduction



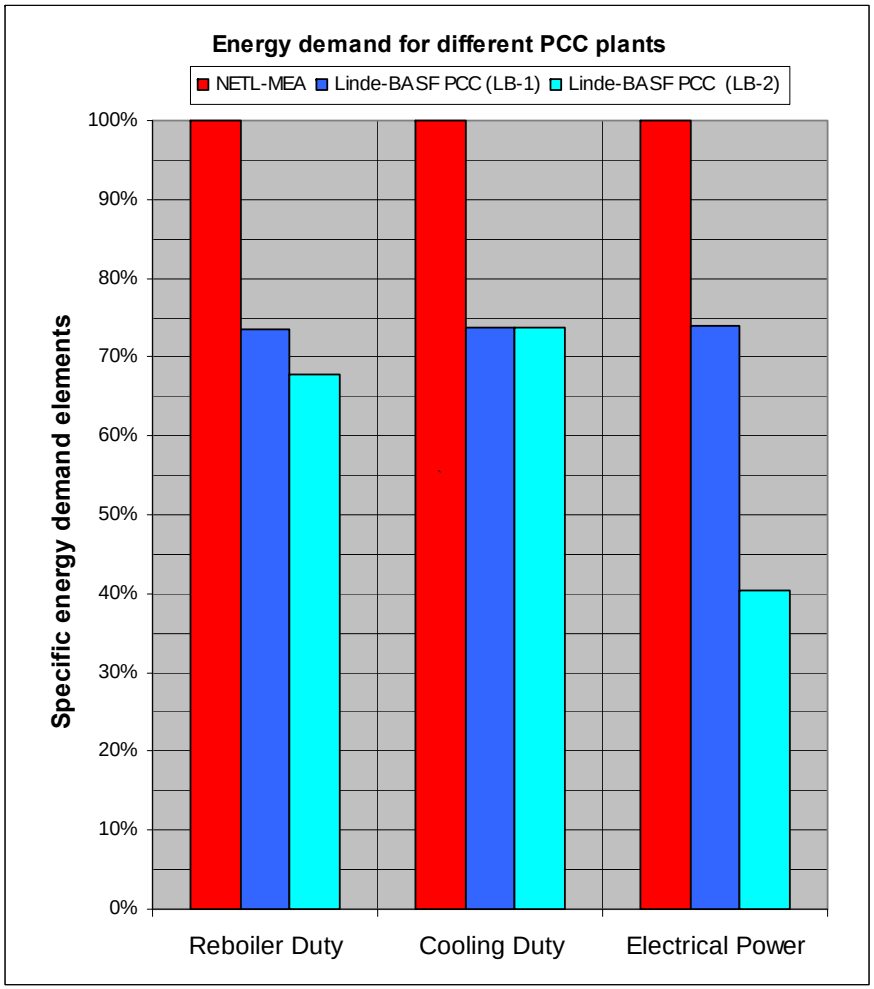
Linde-BASF advanced PCC plant design*

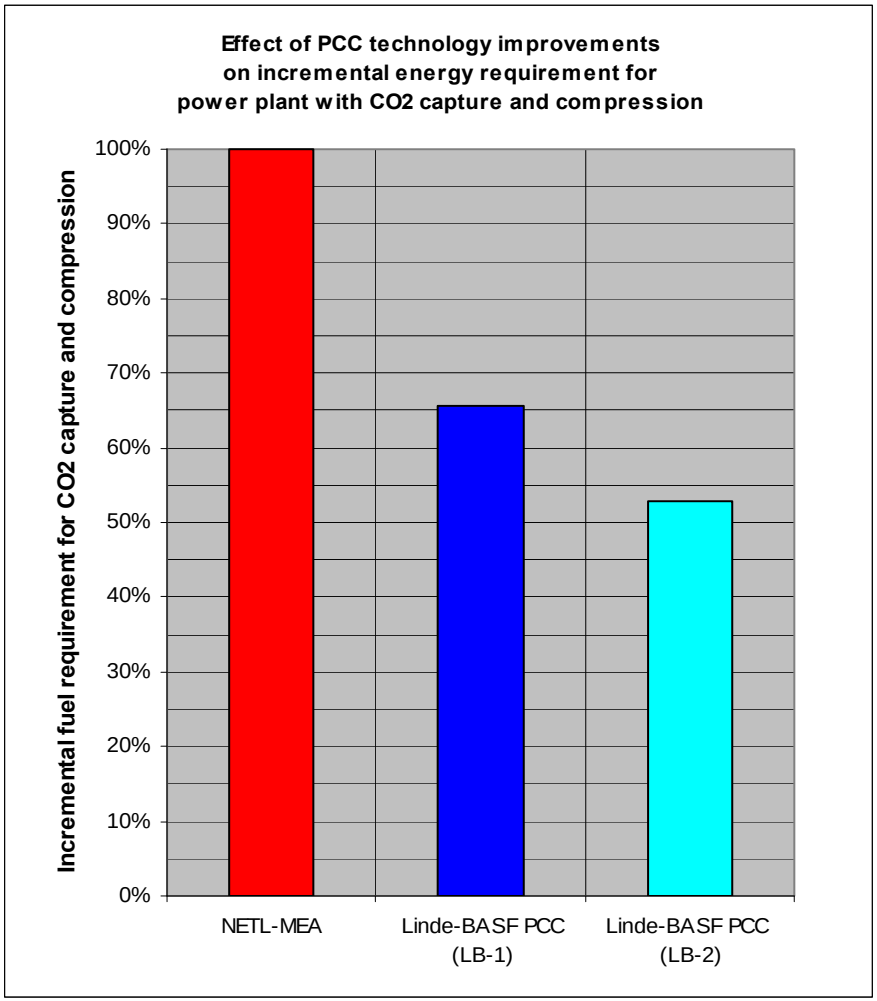


•Patent Applications 2010-2012

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

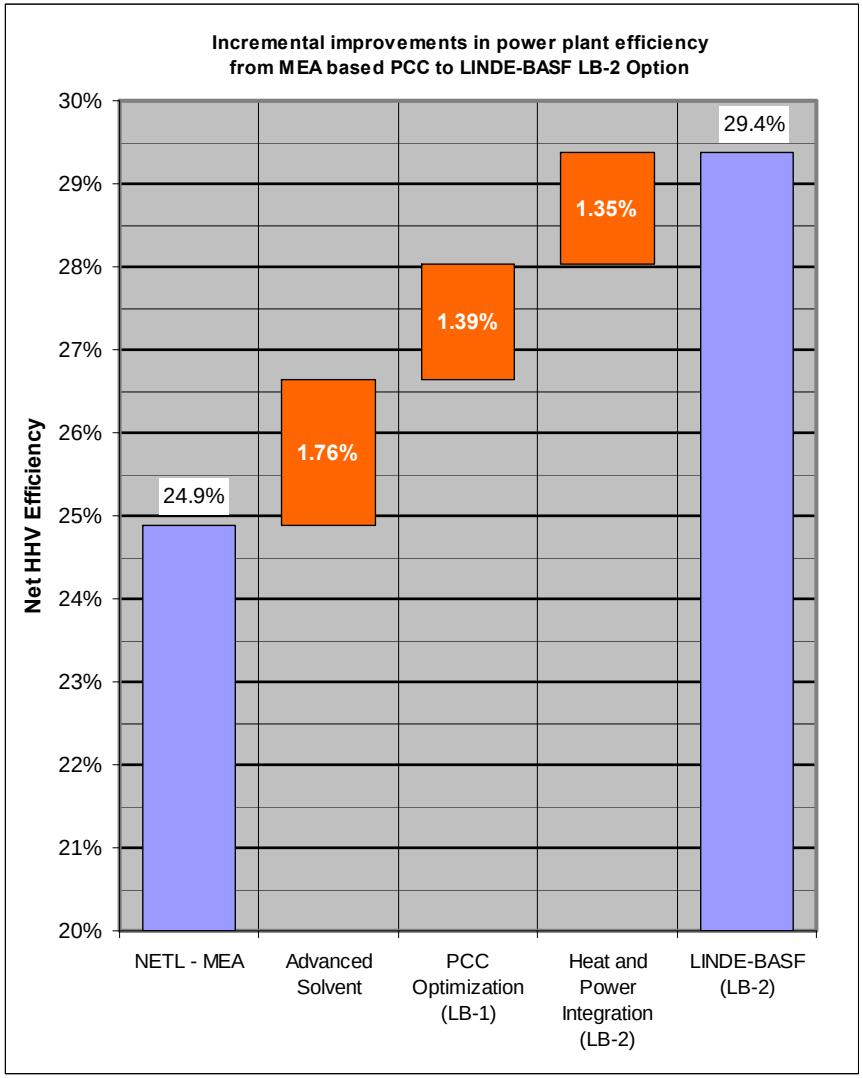
Comparative PCC Performance Results
Linde-BASF vs Reference DOE/NETL Case*

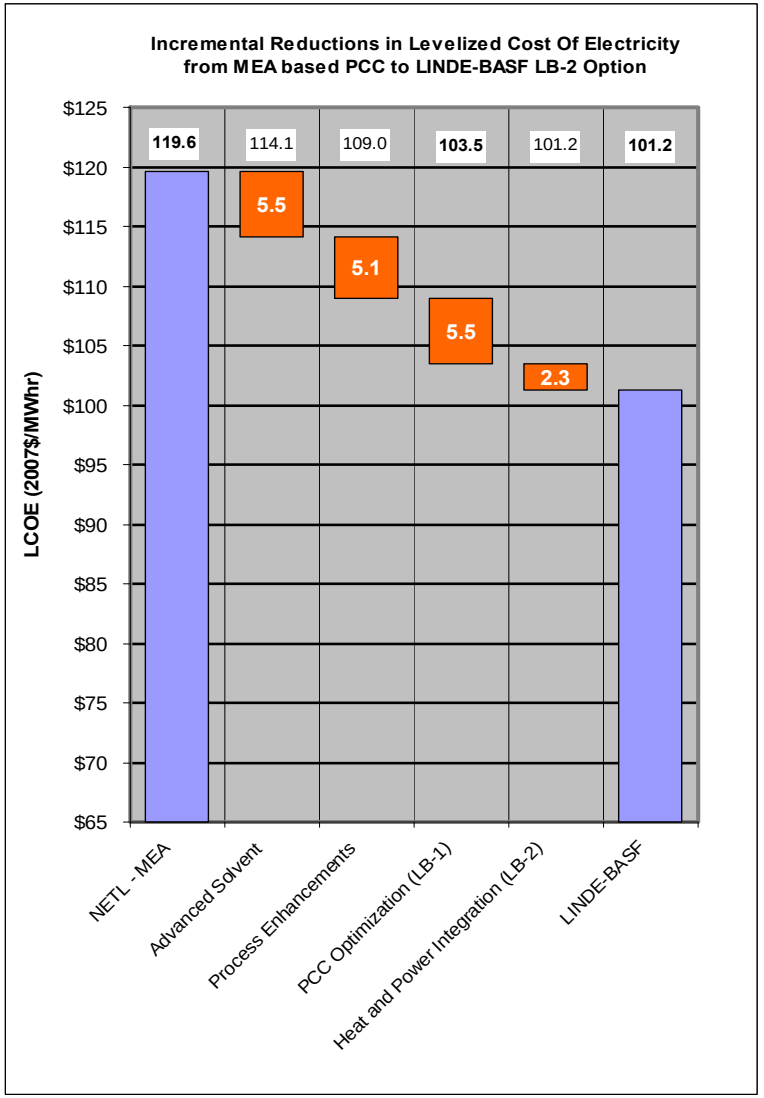




* Reference Case # 10 of DOE-NETL 2007/1281 Report

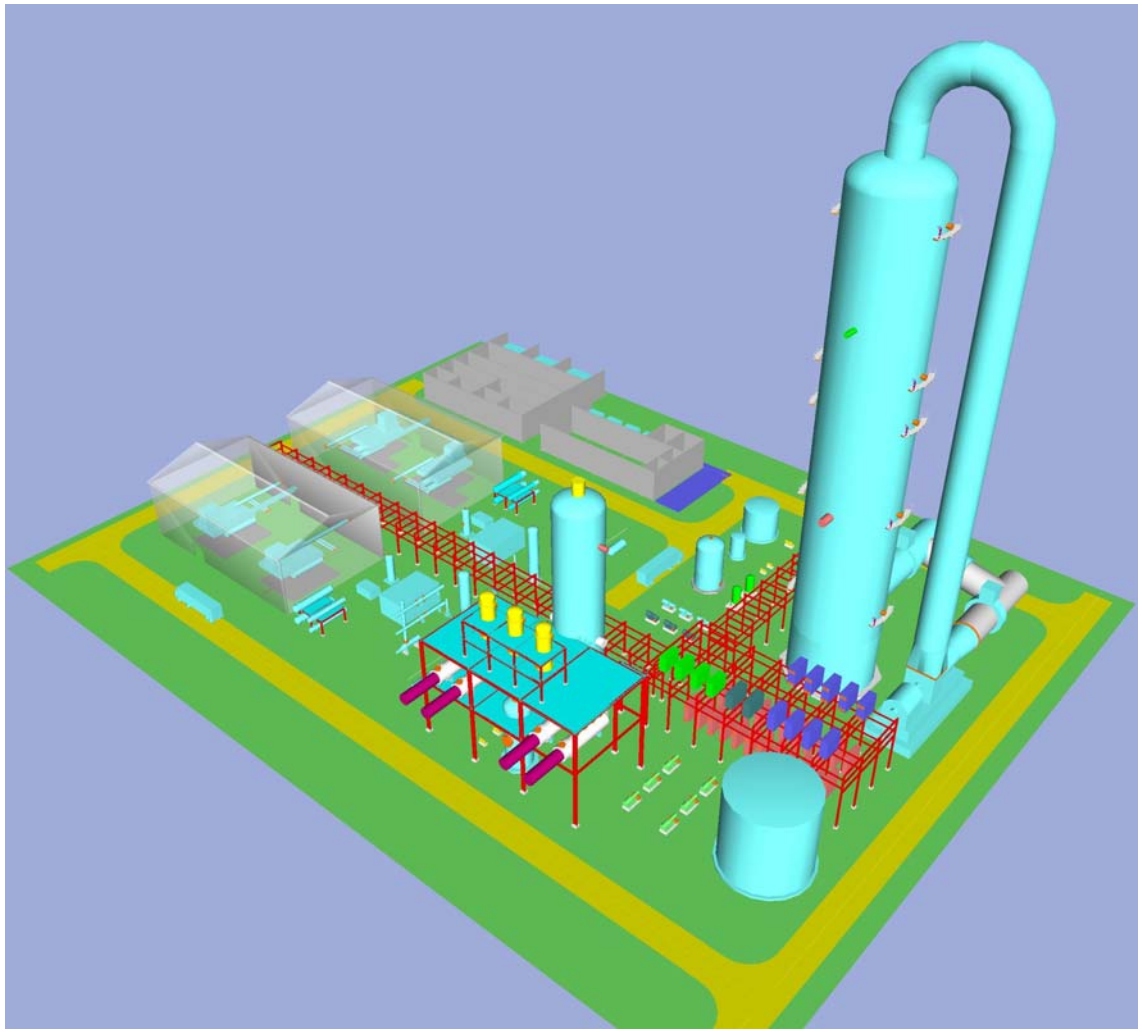
Power plant efficiency improvements and LCOE reductions with Linde-BASF PCC technology





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

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

Linde-BASF experience in large scale carbon capture

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

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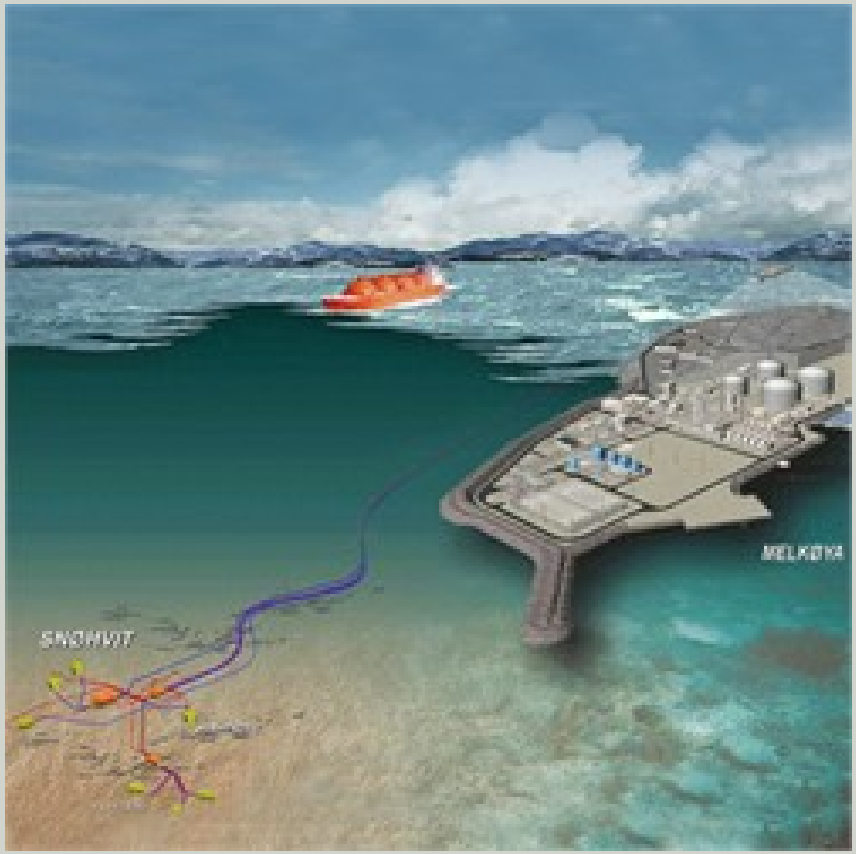
World's first industrial project to deliver CO_2 separated onshore from the well-stream back offshore for re-injection into a reservoir

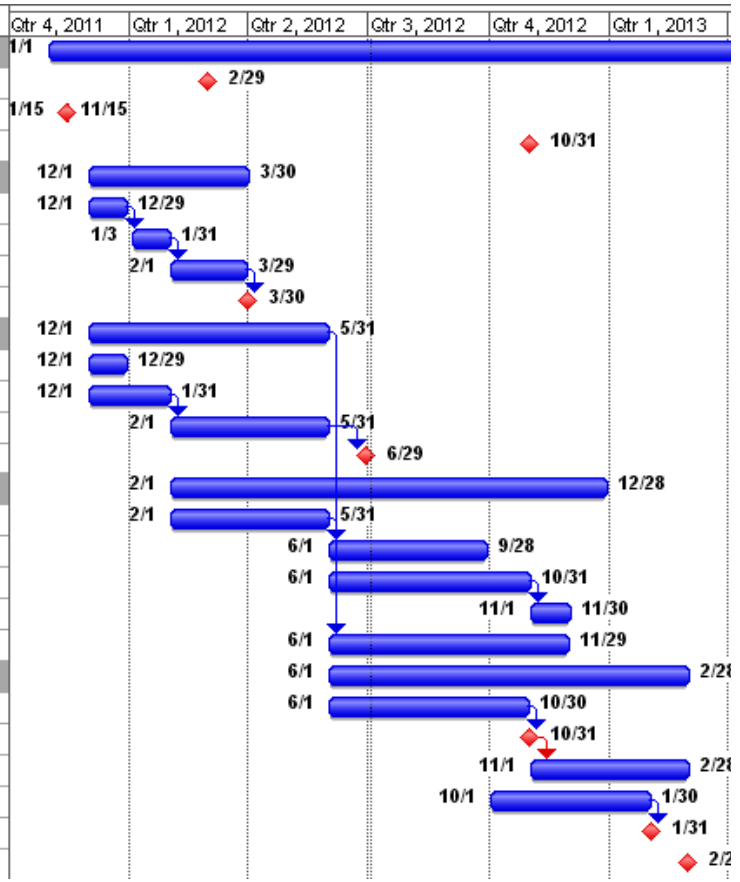
- Partnership with StatoilHydro Petroleum
- Melkoya island near the town of Hammerfest, Norway
- CO_2 sequestration and re-injection integral part of the Hammerfest LNG project. **Linde performed design, EPC and commissioning**
- One dedicated well for CO_2 storage in a sandstone formation sealed by 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)



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 1 tasks successfully completed on time and on schedule

Project Schedule and Milestones: Budget Period 2

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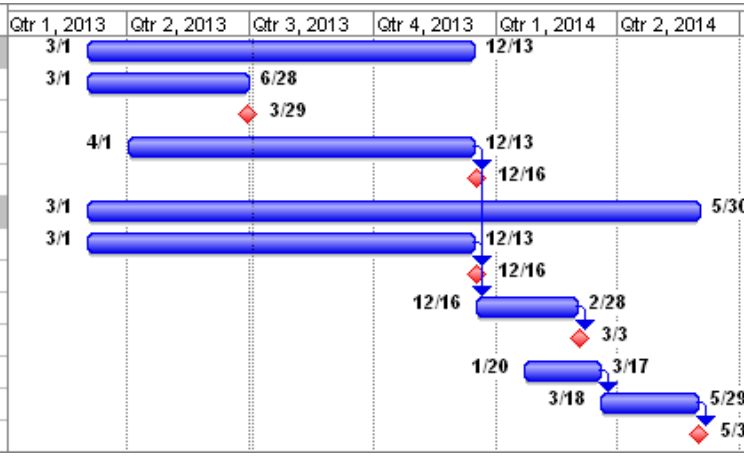
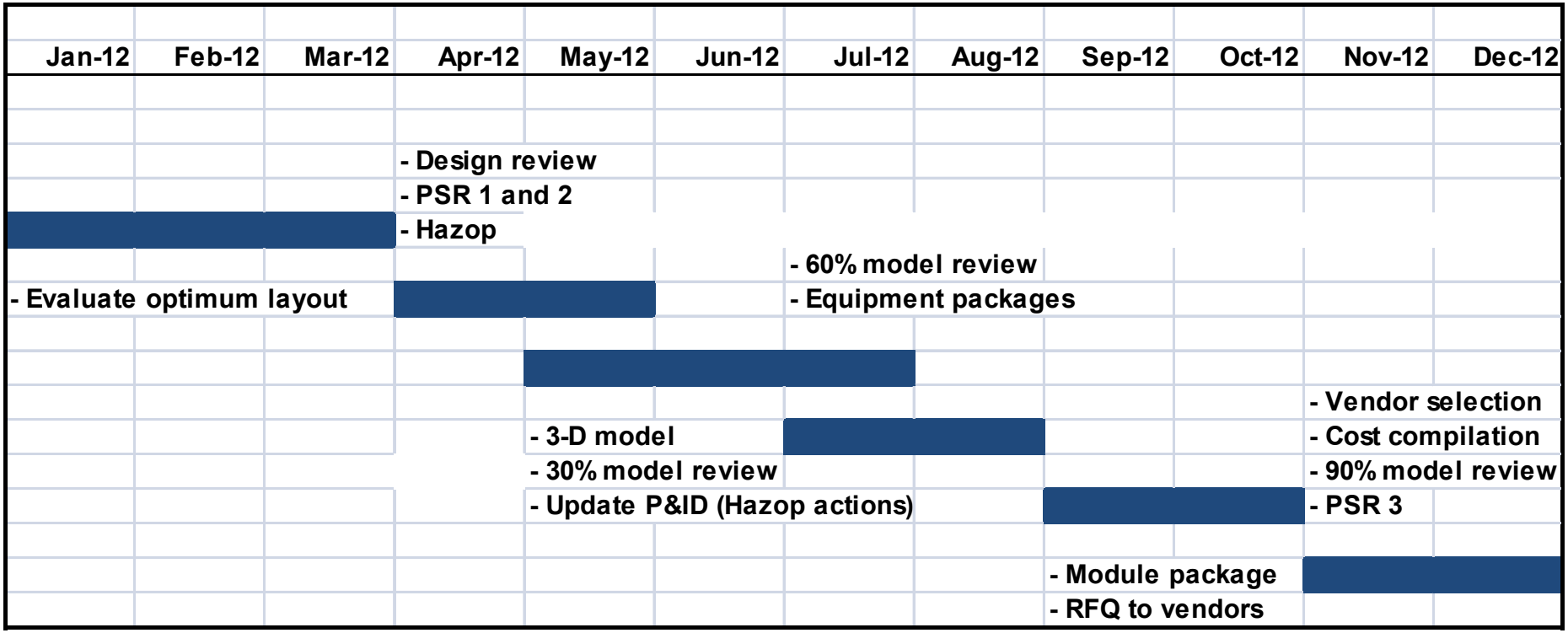
ID	Task Name
28	**6. Supply of equipment and materials**
29	6.1 Equipment proocurement
30	**h. Complete purchase orders and fabrication contracts for the 1 MWe pilot plant**
31	6.2 System fabrication
32	**i. Complete shop fabrication of equipment and modules and associated engineering checks**
33	**7. Plant construction and commissioning**
34	7.1 Site preparation and foundations
35	**j. Complete site preparation and foundation installation at NCCC and receive pilot plant**
36	7.2 Receiving and installation of plant modules
37	**k. Complete installation of the 1 Mwe pilot plant (columns and modules) at NCCC**
38	7.3 Tie-ins within modules and to feeds and utilities
39	7.4 Final ES&H review and commissioning of equipment
40	**l. Mechanical completion of 1 MWe pilot unit at NCCC**



Budget Period 2 tasks initiated in March 2013 and are currently in progress

Detailed engineering timeline: Key dates



PSR: Process Safety review; P&ID: Process and Instrumentation Diagrams; RFQ: Request for quotes;
Hazop: Hazard and operability study

Task 3: Design Selection
Pilot Plant Layout

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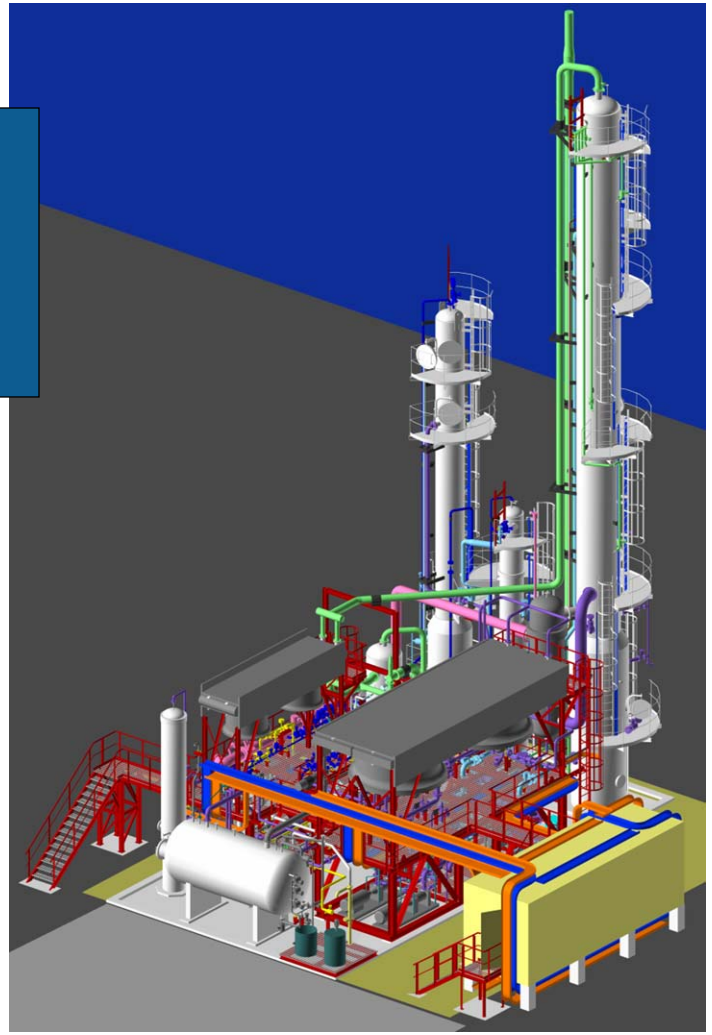
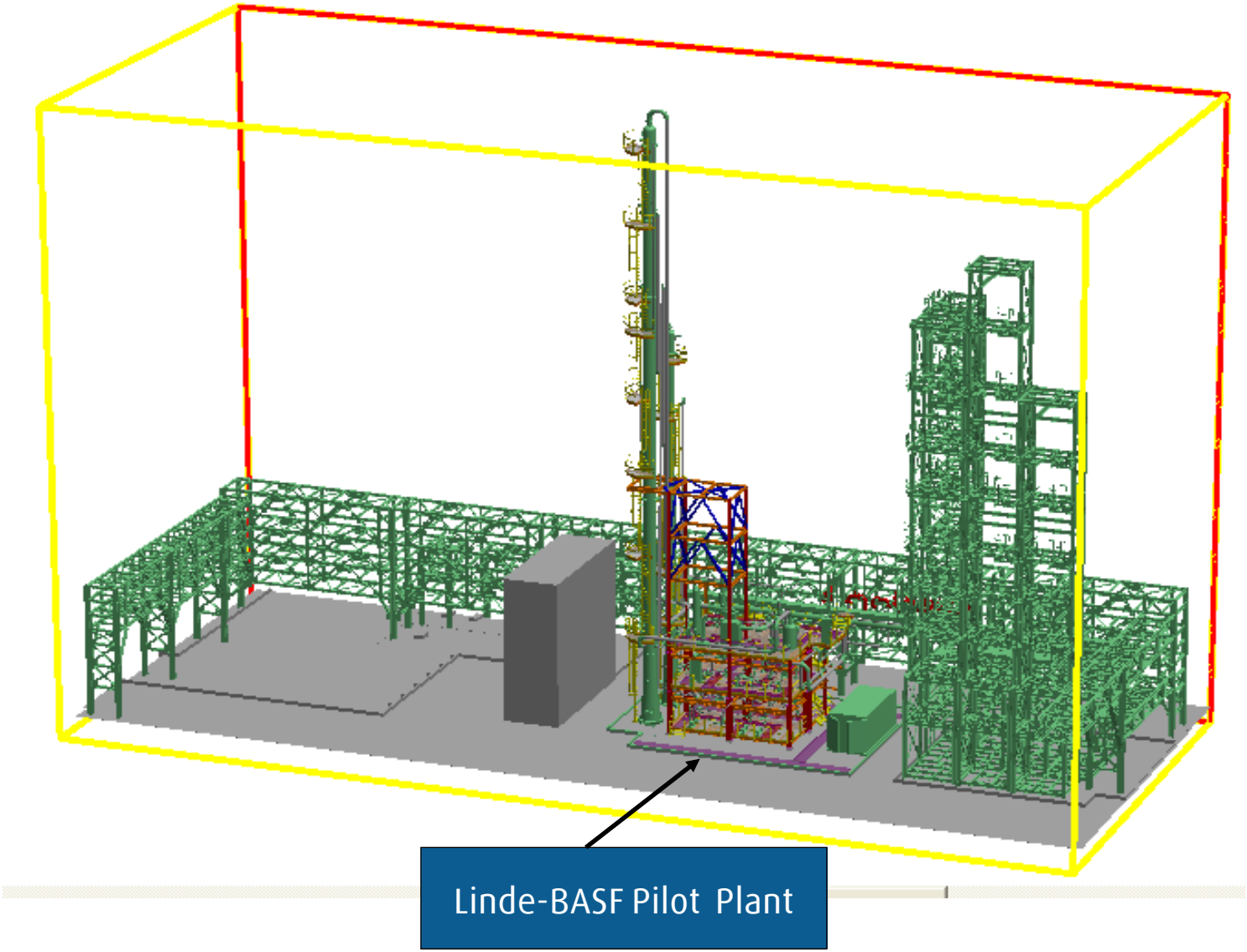
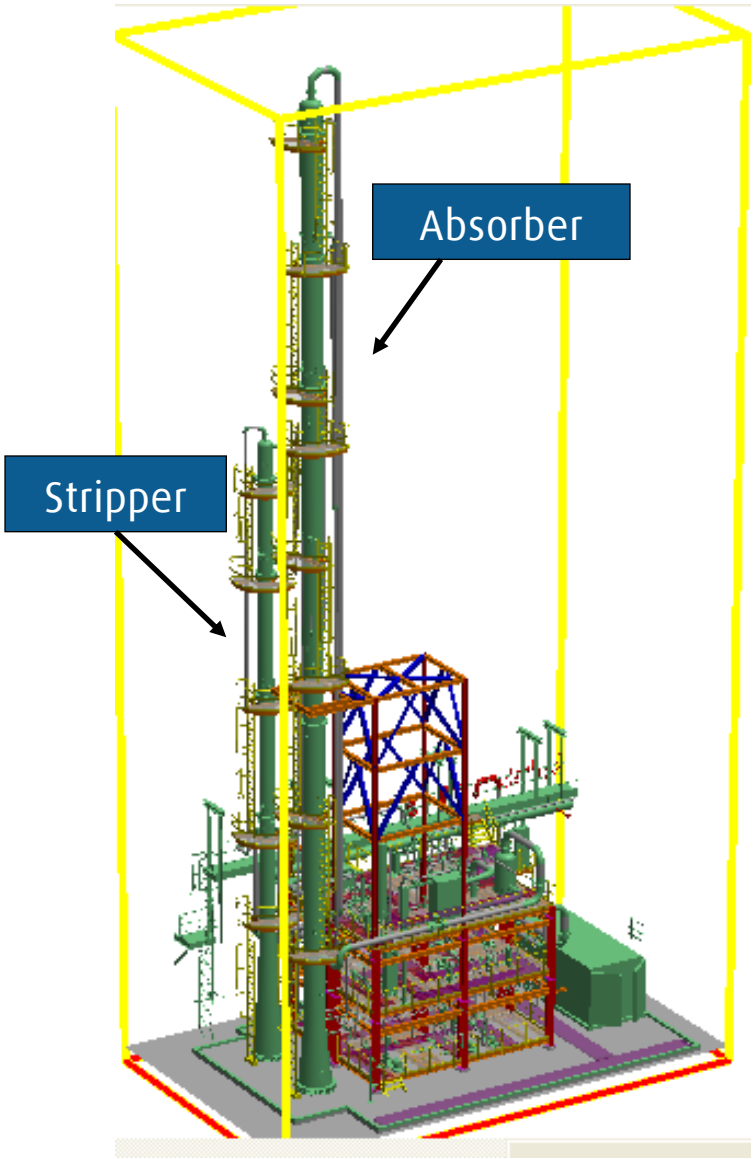
Optimized plant layout investigated

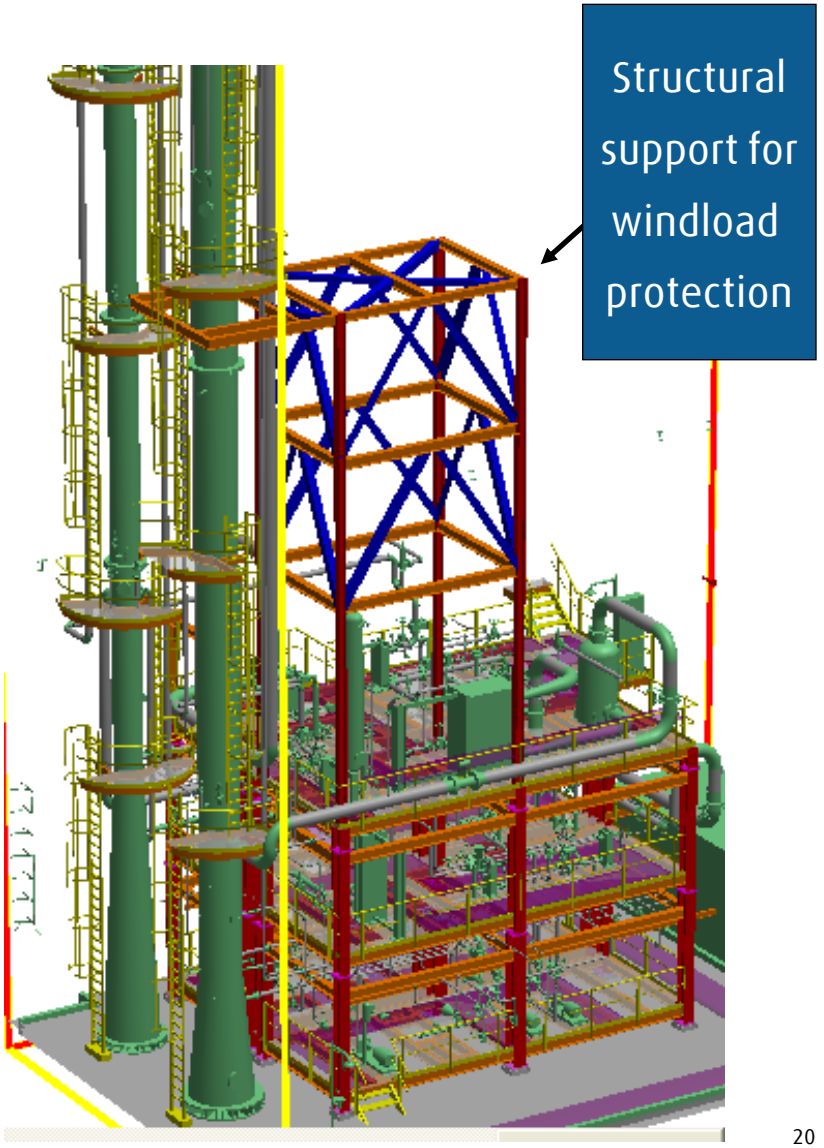


3D Model of NCCC site with Linde-BASF Pilot Plant

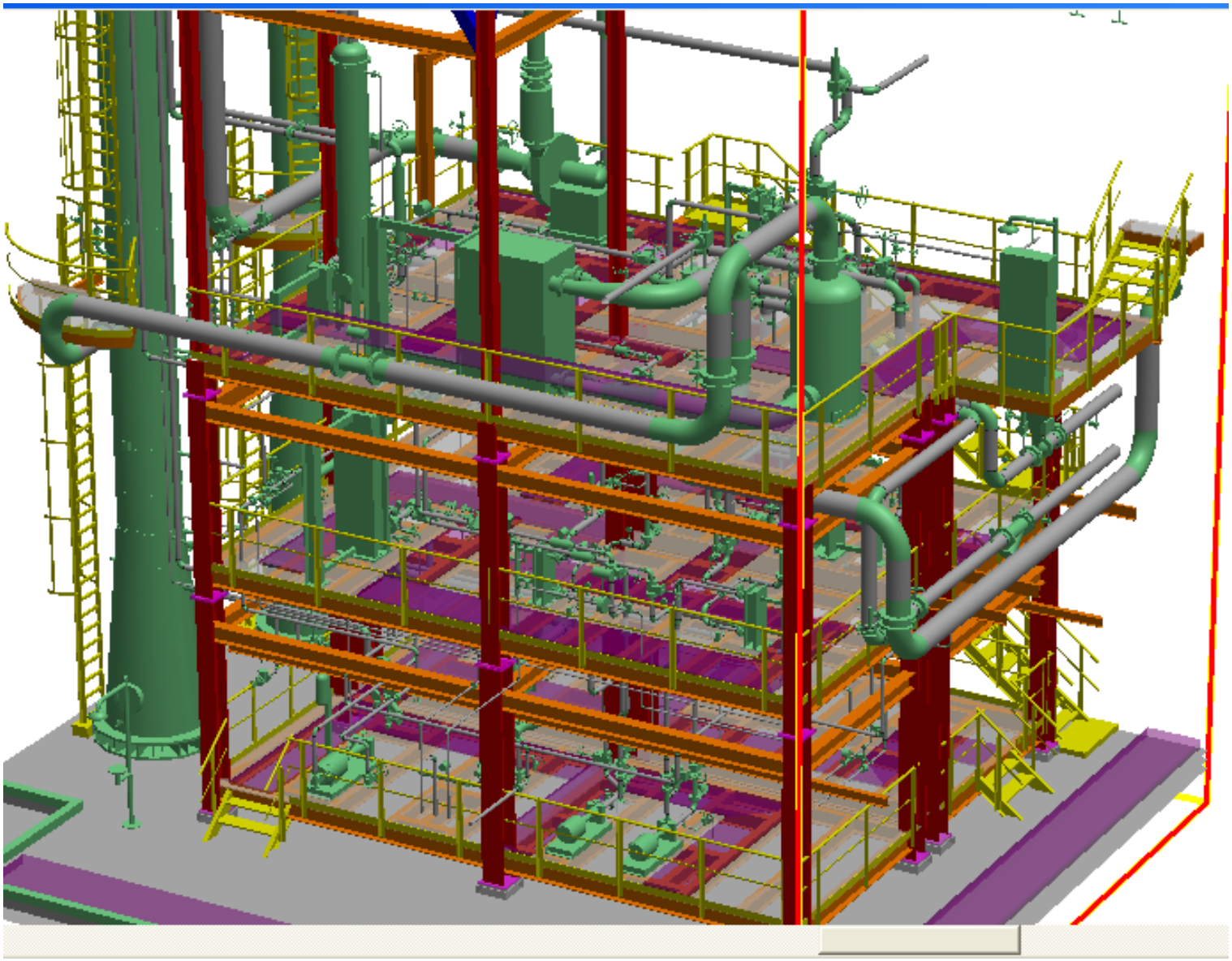


3D Model of Linde-BASF 1 MWe Pilot Plant





3D Model of Linde-BASF Pilot Plant modular design (3 level structure)



Project progress: Key Project Milestones (Budget Period 1) Status

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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 - completed 01/09/2013 √
- Complete initial EH&S assessment - Completed 12/14/2012 √
- Complete detailed pilot plant engineering and cost analyis for the 1 MWe pilot plant to be tested at NCCC – Completed by 02/15/2013 √

Project continuation request to proceed to Budget Period 2 was presented to DOE-NETL on Jan 14, 2013 and was accepted.

Key design and engineering features and decisions

- Joint design basis development (Linde/BASF and SCS/NCCC) for the nominal 1 MWe pilot plant
- Leveraged Niederaussem pilot plant experience for early design selection decision on target solvent, pilot plant preliminary sizing, process control and analytical sampling and measurement
- Pilot plant maximum testing capability to 30 TPD CO2 or 1.5 MWe equivalent – confirmed utility availability with some upside margins
- Integrated modeling approach for detailed engineering – start with the existing NCCC facility model with tie-in points defined and integrated into pilot plant model to avoid conflicts in build phase
- Equipment and module packages sent to multiple vendors and vendor selection performed based on cost, capability and eagerness for involvement in project
- Concrete column sections evaluated but determined to impact project timeline significantly – currently allowing for future swapping the SS bottom section of absorber with concrete section.
- Current pilot plant equipment procurement and build schedule (BP2) requires BP2 timeframe extension by 3-months. No cost time extension agreed with DOE-NETL.

Status against Budget Period 1 decision point success criteria

Decision Point	Basis for Decision/Success Criteria	Status
Completion of Budget Period 1	Successful completion of all work proposed in Budget Period 1	Completed
	Demonstrate a 10% reduction in capital costs with Linde-BASF CO2 capture process	30.5 to 34.7% for PCC and 16.6 to 17.3% for integrated power plant
	Demonstrate a LCOE increase of less than 65% over the baseline	62.2% and 58.8% for 2 options considered
	Submission of an Executed Host Site Agreement	Completed
	Submission of a Topical Report – Initial Techno-Economic Analysis	Completed
	Submission of a Topical Report – Initial EH&S Assessment	Submitted
	Submission of a Topical Report – Detailed Pilot Plant Engineering and Cost Analysis	Submitted
	Submission and approval of a Continuation Application in accordance with the terms and conditions of the award	Submitted & approved by DOE-NETL

Progress on procurement of pilot plant equipment, modules and site installation contract (Linde Engineering – North America, formerly SFPC)

Item	Progress/Accomplishments to date	Key activity planned for completion
Heat Exchangers	- Production & testing/inspection completed - Shipped to module fabricator	- Installation on modules
Pumps	- Production & perf. testing completed - Performance testing & acceptance	- Installation on modules
Columns and pressure vessels	- Absorber & stripper final drawing complete and approved for production - Other pressure vessels produced	- Produce, inspect and ship to site (Jan 2014) - Ship vessels to module fab.
Column internals	- Order placed. Final drawings complete & approved for production.	- Produce & ship for assembly in column
Modules	- Order finalized with design updates - Structural steel assembly in progress	- Finish module assembly - Ship to site (Dec 2013)
Site installation contract	- Contractor finalized and terms agreed	- Construction team mobilization at site (Oct. 2013)
Instruments, control valves, analyzers and other	- Order placed for all items - Several items shipped to module fab.	- Install on modules - Selected items direct to site

Specification and Purchase of Process Equipment for the Pilot Plant

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Heat Exchangers

- Order placed for all HX
- Produced by vendor
- Tested & inspected at vendor site
- Shipped to module fabricator

Plate frame Heat Exchangers

Process and Cooling Water Pumps

- Order placed for all pumps
- Produced by vendor
- Tested & inspected at vendor site
- Shipped to module fabricator

Process Pumps

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

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Steel structures in shop fabrication

Module installation & Assembly

Accomplishments to date (Module):

1. Detailed specifications and 3-D models of the module packages completed.
2. Purchase orders completed and vendor packages received and reviewed.
3. Modules are currently in fabrication.

Planned work by module fabricator:

1. Complete structural assembly.
2. Install equipment and piping, instruments, electrical etc.
3. Test fit and inspection.
4. Shipment to site scheduled for Dec. 2013.

NCCC site preparation to accept pilot plant

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Rebar Placement

Foundations and Slab Complete

Accomplishments to date (SCS at NCCC site):

1. Civil design engineering completed.
2. Micro-pile installation, form and pouring foundation completed.
3. FRP flue gas header designed & installed.
4. Sump pump, flue gas blower, pre-scrubber packing and internals purchased.

Planned work by SCS (July 2013 to Feb 2014):

1. Install epoxy coating on slab and sump pumps.
2. Install blower and pre-scrubber internals and test performance.
3. Install solvent system modifications.
4. Install new impeller for demin water pump.

Key Project Milestones (Budget Periods 2 and 3)

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Budget Period 2 (Mar. 1, 2013 – May 31, 2014)

- Complete purchase orders and fabrication contracts for the 1 MWe pilot plant (06/30/2013)
- Complete shop fabrication of equipment and modules and associated engineering checks (12/15/2013)
- Complete site preparation and foundation installations at NCCC to receive pilot plant (11/15/2013)
- Complete installation of the 1 MWe pilot plant at NCCC (02/28/2014)
- Mechanical completion of 1 MWe pilot plant at NCCC (05/28/2014)

Budget Period 3 (Jun. 1, 2014 – Feb. 28, 2016)

- Complete pilot plant start up and demonstrate plant operation at steady state (08/31/2014)
- Develop pilot-scale parametric test plan (09/30/2014)
- Complete 1 MWe pilot-scale parametric tests (02/28/2015)
- Develop pilot-scale long duration test plan (03/31/2015)
- Complete 1 MWe pilot-scale long duration tests (11/30/2015)
- Complete updated techno-economic analysis (01/31/2016)
- Complete updated EH&S assessment (02/28/2016)

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
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Krish R. Krishnamurthy, Linde LLC
July 8-11, 2013
Pittsburgh, PA