Large Pilot Testing of Linde-BASF Advanced Post-Combustion Carbon Dioxide Capture Technology at a Coal-Fired Power Plant

primary project goal

The University of Illinois is evaluating the design, construction, and operation of a 10 megawatt-electric (MWe) capture system based on the Linde-BASF advanced amine-based post-combustion capture technology at a coal-fired power plant. The project consists of three phases. Phase I was completed and consisted of a feasibility study that outlined preliminary engineering designs, conducted preliminary analysis of National Environmental Policy Act (NEPA)-related issues, and concluded selection of a host site for Phases II and III. Following Phase I, the project completed Phase II, which consisted of a detailed front-end engineering design (FEED) study, completing the NEPA Final Environmental Assessment (EA) with Finding of No Significant Impact (FONSI), and securing recipient cost-share commitments for Phase III. Phase III efforts are underway, consisting of detailed engineering, procurement of equipment and modules, construction and installation of the capture system, and operating test campaigns.

technical goals

Phase I objectives were to:

- Establish the feasibility of installing a 10-MWe capture facility at one of three potential pilot host sites.
- Select a host site based on the feasibility studies.
- Complete an Environmental Information Volume for each potential host site.
- Obtain necessary commitments from the selected site.
- Update the preliminary cost and schedule estimates provided in the Phase I proposal.
- Secure cost-share commitments for Phase II (Design) and develop a plan for securing cost-share commitments for Phase III (Construction/Operation).

Phase II objectives were to:

- Complete a FEED study for the proposed large-scale pilot, including a detailed cost and schedule estimate for Phase III for the installation of the 10-MWe pilot plant at the host site, followed by commissioning, start-up, operations, testing, and data collection for performance validation.
- Complete NEPA process at the host site.
- Draft permitting documentation to be submitted to appropriate authorities to initiate the permitting process and develop a clear understanding of timelines that will support Phase III.
- Document secured cost share for Phase III.
- Secure commitments for all necessary Phase III team members, including an engineering, procurement, and construction (EPC) firm to complete construction.

program area:
Point Source Carbon Capture

ending scale:
Large Pilot

application:
Post-Combustion Power Generation PSC

key technology:
Solvents

project focus:
Linde-BASF CO_2 Capture Process for Coal-Fired Power Plants

participant:
University of Illinois at Urbana-Champaign

project number:
FE0031581

Predecessor projects:
FE0026588
FE0007453

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Linde plc; Affiliated Construction Services; Affiliated Engineers Inc.; Visage Energy

start date:
04.04.2018

percent complete:
70%

- Update the techno-economic analysis (TEA) for the Linde-BASF technology integrated with a 550-MWe net supercritical pulverized coal power plant based on the most recent system design and cost information.

Phase III objectives are to:

- Complete construction of the 10-MWe capture system.
- Operate the system over the upcoming five years and compare the results with the 1.5-MWe testing at the National Carbon Capture Center (NCCC).
- Complete a full TEA for the upscaled plant.
- Perform a risk factor analysis.

technical content

The Linde-BASF advanced CO_2 capture process incorporating BASF's novel amine-based solvent, OASE® blue, with Linde's process and engineering innovations allows for a significant increase in energy efficiency and reduced cost for CO_2 recovery from coal-based power plants. In addition to a reduction in regeneration energy and a lower solvent circulation rate enabled by the BASF solvent, Linde has achieved significant improvements in process design, as shown in Figure 1, featuring an advanced stripper inter-stage heater design to optimize heat recovery in the process. This results in lower capital and operating costs for the CO_2 capture system. The Linde-BASF technology addresses all the major challenges for solvent-based carbon capture, including: (1) high specific energy for regeneration, (2) lack of stability due to thermal and oxidative degradation, (3) increased corrosiveness with increased CO_2 loading, and (4) lack of tolerance to impurities from coal combustion products. The design parameters for the solvent are shown in Table 1.

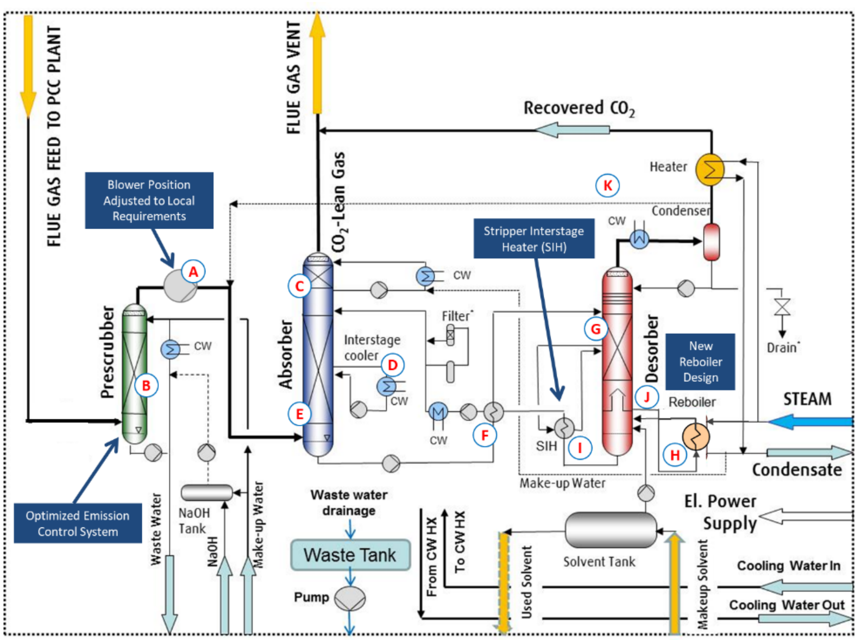

Figure 1: Large pilot process configuration for Linde-BASF technology with Highlighted design improvements.

A. Flue gas blower provides enough pressure to overcome the pressure drop across the pre-scrubber and absorber.

B. Integrated pre-scrubber and direct contact cooler to reduce SO_X content below 5 ppm and simultaneously cool the flue gas stream to ~35–40°C.

C. Innovative and patented water wash section at the top of the column to reduce amine losses, even in the presence of aerosols.

D. A gravity-driven inter-stage cooler for the absorber that eliminates the pump and the controls.

E. High-capacity structured packing reduces the absorber diameter, thereby enabling a larger single-train plant construction.

F. Solvent-based heat exchanger designed to operate over a wide range of temperature approaches, which provides the opportunity to optimize the performance and capital cost trade-off.

G. Regenerator designed for operation at pressures up to 3.4 bar(a), significantly reduces CO_2 compression energy and eliminates the bulky first stage of the CO_2 compressor train, resulting in capital cost savings.

H. Innovative plate and frame design of the reboiler minimizes thermal degradation of solvent and provides for a lower solvent inventory and faster dynamics to respond to power plant load changes.

I. Stripper Inter-Stage Heater (SIH) enhances energy-efficient CO_2 stripping from the solvent by recovering heat from the lean solvent to provide intermediate reboil, thereby reducing energy consumption of solvent regeneration.

J. Variations of the stripper-reboiler flashing configuration, which are being evaluated for an ultimate reduction of solvent regeneration energy.

K. Optional CO_2 recycle stream, provided to evaluate the effect of plant loading and variable CO_2 concentration in the flue gas on overall energy consumption, and to limit the effects of power plant loading on flue gas CO_2 mol% fluctuations.

TABLE 1: SOLVENT PROCESS PARAMETERS

Pure Solvent	Units	Current R&D Value	Target R&D Value
Molecular Weight	mol^{-1}	proprietary	proprietary
Normal Boiling Point	°C	proprietary	proprietary
Normal Freezing Point	°C	proprietary	proprietary
Vapor Pressure @ 15°C	bar(a)	proprietary	proprietary

Manufacturing Cost for Solvent	\$/kg	—	—
Working Solution			
Concentration	kg/kg	proprietary	proprietary
Specific Gravity (15°C/15°C)	—	proprietary	proprietary
Specific Heat Capacity @ STP	kJ/kg-K	proprietary	proprietary
Viscosity @ STP	cP	proprietary	proprietary
Absorption			
Pressure	bar(a)	1.0	0.9-1.1
Temperature	°C	30-70	30-60
Equilibrium CO_2 Loading	mol/mol	proprietary	proprietary
Heat of Absorption	kJ/mol CO_2	proprietary	proprietary
Solution Viscosity	cP	proprietary	proprietary
Desorption			
Pressure	bar(a)	1.6-3.4	1.6-3.4
Temperature	°C	124-140	124-140
Equilibrium CO_2 Loading	mol/mol	proprietary	proprietary
Heat of Desorption	kJ/mol CO_2	proprietary	proprietary
Proposed Module Design		*(for equipment developers)*	
Flue Gas Flowrate	kg/hr	LB1 Case: 2,718,270	SIH Case: 2,674,784
CO_2 Recovery, Purity, and Pressure	% / % / bar(a)	90%, 99.98% (dry), 3.4 bar(a)	90%, 99.98% (dry), 3.4 bar(a)
Absorber Pressure Drop	bar	0.1	
Estimated Absorber/Stripper Cost of Manufacturing and Installation	$\frac{\$}{kg/hr}$	proprietary	

Previous testing of a 0.45-MWe pilot plant incorporating the Linde-BASF technology and utilizing lignite-fired power plant flue gas has shown that the OASE blue solvent is stable, with little degradation observed over 55,000 hours, whereas the reference monoethanolamine (MEA) solvent started to degrade appreciably under the same conditions after 2,000 hours. The Linde-BASF CO_2 capture process was also previously tested at 1.5-MWe-scale at NCCC under project DE-FE0007453, supported by the U.S. Department of Energy (DOE). The study validated solvent stability and demonstrated a cyclic capacity 20% higher than MEA and regenerator steam consumption 25% lower than MEA. These results confirmed the ability of this technology to be cost-effective, energy efficient, and compact. This project leverages work done previously through a DOE Phase I grant (DE-FE0026588), in which a 15-MWe pilot plant of the Linde-BASF advanced CO_2 capture technology was designed to be integrated with the University of Illinois' Abbott Power Plant on the campus of the University of Illinois at Urbana-Champaign (UIUC), with the goal of capturing approximately 300 tonnes per day (tpd) of CO_2 at a 90% capture rate. The 15-MWe pilot project aimed to optimize the process at larger scale and gather performance data under realistic conditions to enable a robust commercial design. Phase I of the project resulted in the completion of a preliminary plant design with basic engineering and cost estimates; establishment of permitting needs; identification of approaches to address environmental, health, and safety concerns related to pilot plant installation and operation; and completion of a detailed TEA, demonstrating that the implementation of Phase II (Detailed Design, Construction, and Operation) of the project is feasible. The project also established strategies for workforce development for the operation and maintenance of carbon capture systems based on the Linde-BASF technology that are retrofitted to existing power plants.

The design and costing of the 10-MWe capture plant for installation at the selected host site (City Water, Light, and Power [CWLP] coal-fired power plant in Springfield, Illinois) was based on the estimate for the 15-MWe pilot in the previous DOE-funded project and established industry-scaling factors. The capture system will be installed in the Dallman 4 unit, which is a nominal 200-MWe pulverized coal-fired unit that became operational in 2009. The unit employs a Foster Wheeler front and rear wall-fired pulverized coal boiler equipped with low-nitrogen oxide (NO_X) burners; a selective catalytic reduction (SCR) unit for NO_X removal; a hydrated lime injection (HLI) system for sulfur trioxide (SO_3) removal; a fabric baghouse to capture particles; a flue gas desulfurization (FGD) system to mitigate sulfur dioxide (SO_2) emissions; and a wet electrostatic precipitator (ESP) to remove liquid droplets, such as sulfuric acid mist. For the 10-MWe capture pilot, a slipstream of flue gas from the Dallman 4 unit will be utilized as a feed gas for CO_2 capture.

Based on results from small pilot studies and the TEA, the technology will achieve high CO_2 capture (≥90%) and generate high-purity (>99.9%) captured CO_2 in a cost-effective manner. TEA results indicated that when the proposed advanced Linde-BASF technology is integrated with a 650-MWe net supercritical pulverized coal power plant, there will be an increase in power plant efficiency of approximately 1.2 percentage points, a nominal 12.6% reduction in COE, and 26.3% reduction in cost of CO_2 capture ($/MT) compared to the latest DOE/National Energy Technology Laboratory (NETL) base case (Case B12B reference). A summary of the expected economics results is shown in Table 2.

TABLE 2: POWER PLANT CARBON CAPTURE ECONOMICS

Economic Values	Units	Current R&D Value	Target R&D Value
Cost of Carbon Captured	$/megatonne CO_2	$55.60	$41.01
Cost of Carbon Avoided	$/megatonne CO_2	n/a	n/a
Capital Expenditures	$/MWhr	$50.98	$40.18
Operating Expenditures	$/MWhr	$54.24	$50.70
Cost of Electricity	$/MWhr	$114.12	$99.78

Definitions:

Cost of Carbon Captured – Projected cost of capture per mass of CO_2 captured under expected operating conditions.

Cost of Carbon Avoided – Projected cost of capture per mass of CO_2 avoided under expected operating conditions.

Capital Expenditures – Projected capital expenditures in dollars per unit of energy produced.

Operating Expenditures – Projected operating expenditures in dollars per unit of energy produced.

Cost of Electricity – Projected cost of electricity per unit of energy produced under expected operating conditions.

Bar(a) – Unit used to indicate absolute pressure, where the reference pressure is absolute zero, i.e., not taking into account atmospheric pressure.

STP – Standard temperature and pressure (15°C, 1 atmosphere [atm]).

Pure Solvent – Chemical agent(s), working alone or as a component of a working solution, responsible for enhanced CO_2 absorption (e.g., MEA in an aqueous solution).

Manufacturing Cost for Solvent – “Current” is market price of chemical, if applicable; “Target” is estimated manufacturing cost for new solvents, or the estimated cost of bulk manufacturing for existing solvents.

Working Solution – The solute-free (i.e., CO_2-free) liquid solution used as the working solvent in the absorption/desorption process (e.g., the liquid mixture of MEA and water).

Absorption – The conditions of interest for absorption are those that prevail at maximum solvent loading, which typically occurs at the bottom of the absorption column. These may be assumed to be 1 atm total flue-gas pressure (corresponding to a CO_2 partial pressure of 0.13 bar) and 40°C; however, measured data at other conditions are preferable to estimated data.

Desorption – The conditions of interest for desorption are those that prevail at minimum solvent loading, which typically occurs at the bottom of the desorption column. Operating pressure and temperature for the desorber/stripper are process-dependent (e.g., an MEA-based absorption system has a typical CO_2 partial pressure of 1.8 bar and a reboiler temperature of 120°C). Measured data at other conditions are preferable to estimated data.

Pressure – The pressure of CO_2 in equilibrium with the solution. If the vapor phase is pure CO_2, this is the total pressure; if it is a mixture of gases, this is the partial pressure of CO_2. Note that for a typical pulverized coal power plant, the total pressure of the flue gas is about 1 atm and the concentration of CO_2 is about 13.2%. Therefore, the partial pressure of CO_2 is roughly 0.132 atm or 0.130 bar.

Concentration – Mass fraction of pure solvent in working solution.

Loading – The basis for CO_2 loadings is moles of pure solvent.

Estimated Cost – Basis is kg/hr of CO_2 in CO_2-rich product gas; assuming targets are met.

Flue Gas Assumptions – Unless noted, flue gas pressure, temperature, and composition leaving the FGD unit (wet basis) should be assumed as:

Pressure	Temperature	Composition						
		mol%					ppmv	
psig	°F	CO_2	H_2O	N_2	O_2	Ar	SO_X	NO_X
0	135	9.8	17	67	5.3	0.80	34	30

Other Parameter Descriptions:

Chemical/Physical Solvent Mechanism – Carbon dioxide in the flue gas chemically binds to the OASE blue aqueous amine-based solvent via an exothermic absorption step and this chemical bond is broken in the endothermic desorption step via heat provided by steam in the reboiler of the regenerator column, generating pure CO_2.

Solvent Contaminant Resistance – The OASE blue solvent is highly resistant against many contaminants in the flue gas, as shown in both parametric and long-term continuous tests (see Electric Power Research Institute [EPRI] report[1] for additional information).

Solvent Foaming Tendency – During the pilot plant operation, although anti-foaming injection was included in the design, its use was not found necessary.

Flue Gas Pretreatment Requirements – The pretreatment requirement includes reducing sulfur oxide (SO_X) in the flue gas to 2 to 5 parts per million (ppm) in order to limit solvent degradation and is implemented in a direct contact cooler in conjunction with flue gas cooling, typically by adding appropriate amount of sodium hydroxide corresponding to the SO_X present in the flue gas.

Solvent Makeup Requirements – The OASE Blue solvent makeup rate is determined by the sum of the amine losses in the treated gas leaving the absorber column and the rate of solvent degradation during operation over time. Low makeup rates were observed during long-term testing well below an operationally manageable threshold. Low solvent makeup is expected at scale when processing flue gas from power plants with a baghouse filter for particulate removal or with upstream flue gas pretreatment for aerosol mitigation.

Waste Streams Generated – The main waste liquid stream is from the direct contact cooler where SO_X and NO_X are removed; this stream will go through an oxygenation treatment that converts sulfite and bisulfite compounds into sulfate compounds prior to being discharged to the local sanitary district. A small amount of solid waste is removed using an activated carbon filter and mechanical cartridge filter that are replaced at regular intervals. Since the solvent degradation observed in the pilot testing is small, no solvent reclamation unit is envisioned in the large scale.

Process Design Concept – See Figure 1.

Proposed Module Design – Free standing absorber and stripper columns will be tied into a modularized process skid. There will be associated containers for electrical equipment, analytical equipment, and process control.

technology advantages

- Significant reduction in specific regeneration steam consumption (24–40% lower), electrical power (14–26% lower), and cooling water duty (32–43% lower) compared to a reference MEA plant.
- Increased higher heating value efficiency (HHV) for power production (up to ~32.7% efficiency) and lower thermal load compared to a reference MEA plant (28.4% efficiency) due to a combination of advanced solvent and process improvements, including integrated pre-scrubber and direct contact cooler, downstream gas blower, higher desorber pressure, and interstage gravity-flow cooler.
- The total plant costs are ~20% lower compared to a reference MEA plant, with significantly lower post-combustion capture plant capital costs.
- The Linde-BASF technology is readily scalable to large capacities with a single-train system, offering the potential to further reduce costs by utilizing economies of scale.
- BASF is the producer of the OASE Blue solvent and the owner of the solvent technology. A major global player in the chemical industry, BASF has the capabilities to reliably produce and supply the OASE blue solvent in sufficient volumes needed for commercialization, thereby enabling application at scale by avoiding issues related to solvent manufacturing for large-scale commercial plants.

- The Linde-BASF partnership combines the necessary capabilities and experience to deliver the complete CO_2 capture technology value chain from solvent production to full-scale CO_2 capture plant EPC, commercial deployment, and long-term, continuous operations.

R&D challenges

- Scale-up of absorber column at low cost, maintaining uniform vapor and liquid distribution.
- Optimizing operation of the stripper to reduce steam utilization and increase energy efficiency of the CO_2 capture process using advanced stripper configurations and stripper inter-stage heating.
- Managing flue gas impurities and aerosol formation to reduce amine losses.
- Testing of new process units for energy optimization.
- Integration with operations at the CWLP host site.

status

In Phase I, the CWLP coal-fired power plant in Springfield, Illinois, was selected as the host site for the large pilot (10 MWe) capture plant and Phase II cost-share commitments were finalized. Preliminary engineering and cost estimates were prepared for the equipment inside the battery limit (ISBL) and outside the battery limit (OSBL). A NEPA contractor, ICF International Inc., was also selected as part of the Phase I effort. A plan was developed for securing cost-share commitments for Phase III.

In Phase II, a detailed FEED study was performed and completed, including equipment cost estimates. All required NEPA/permitting issues have been resolved and cost-sharing estimates have been finalized.

Phase III is currently underway and is set to conclude in 2026.

available reports/technical papers/presentations

O'Brien, K.C. & Brownstein, S., 2021, "PHASE III: Large Pilot Testing of Linde-BASF Advanced Post-Combustion CO_2 Capture Technology at a Coal-Fired Power Plant (FE-0031581)." Phase III Kickoff Meeting, October 2021.

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O'Brien, K. C., "PHASE II: Large Pilot Testing of Linde-BASF Advanced Post-Combustion CO_2 Capture Technology at a Coal-Fired Power Plant (FE0031581)," Phase II Kickoff Meeting, October 2019.

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Krishnamurthy, K. R., “Development and Scale-up of an Advanced Aqueous Amine-Based Post-Combustion CO_2 Capture Utilizing BASF’s OASE® Blue Technology,” presented at the 2016 Carbon Capture, Utilization, and Storage Conference, Tysons, VA, June 2016.

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Jovanovic, S., et. al., “Slipstream Pilot-Scale Demonstration of a Novel Amine-Based Post-Combustion Technology for Carbon Dioxide Capture from Coal-Fired Power Plant Flue Gas,” Topical Report: Techno-Economic Analysis of 550 MWe subcritical PC power plant with CO_2 capture, May 2012. *https://netl.doe.gov/sites/default/files/2017-12/techno-economic-analysis-topical-rpt-may2012.pdf*.

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[1] BASF-Linde Post Combustion Carbon Capture Pilot Plant at the National Carbon Capture Center, 2016 Test Campaign Results, EPRI, February 2017.