Large Pilot Testing of Linde-BASF Advanced Post-Combustion CO2 Capture Technology at a Coal-Fired Power Plant

DOE/NETL Funding Award DE-FE0031581

Phase I Kick-off Meeting

May 10, 2018

CITY WATER LIGHT AND POWER SPRINGFIELD, IL

ILLINOIS Prairie Research Institute

THE LINDE GROUP Linde

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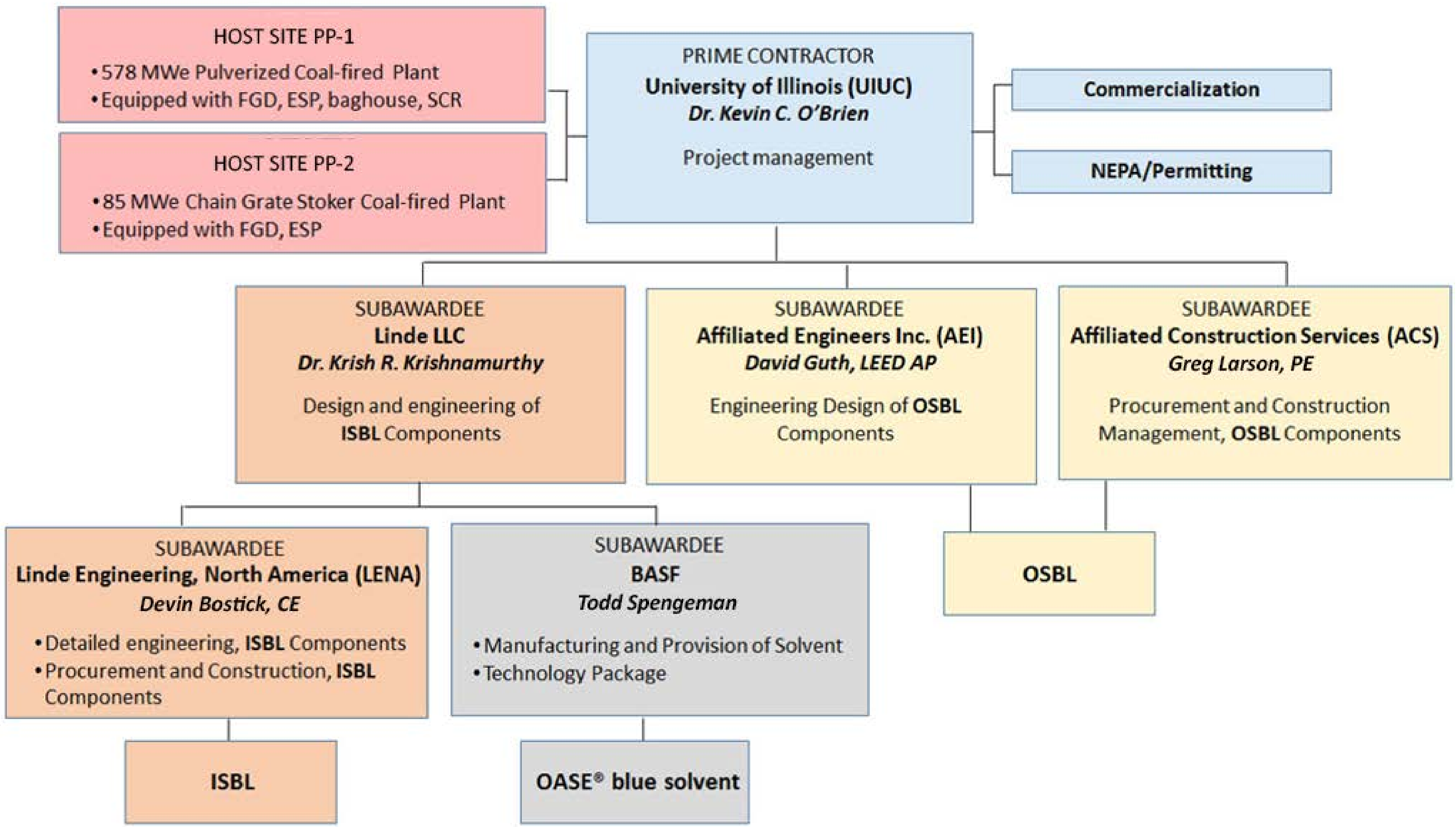
PROJECT MANAGEMENT AND PARTICIPANTS

Objectives for Phase I

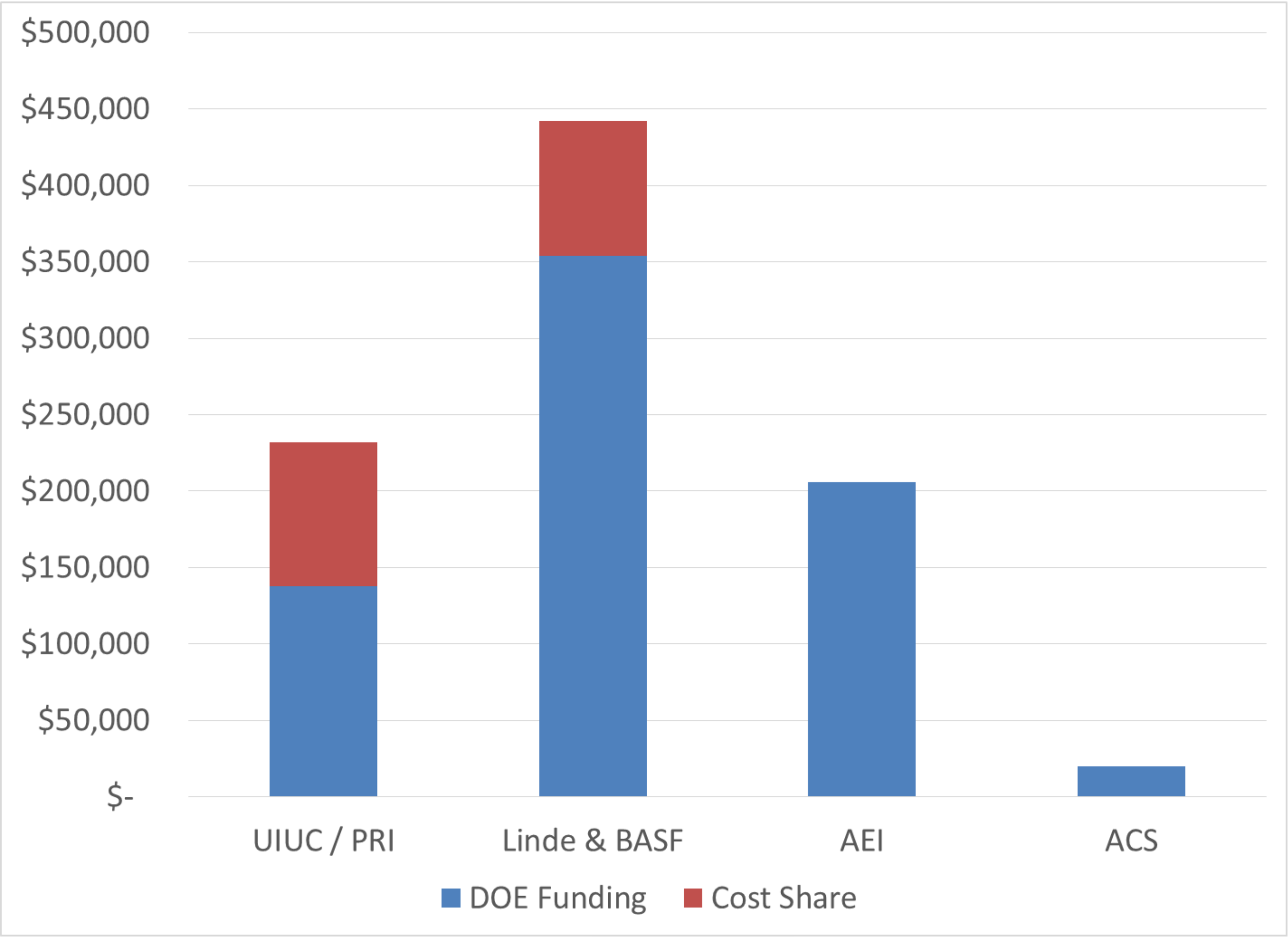
- Establish feasibility of installing a 10 MWe capture facility at one of two potential host
- Select host site
- Complete Environmental Information Volume (EIV) for site
- Obtain commitments from site and team members for Phase II (including NEPA and FEED contractor)
- Update preliminary cost and schedule estimates for Phase II and Phase III
- Secure cost share for Phase II and plan for securing cost share for Phase III

Phase I Team

Well-defined roles based on relevant capabilities



Phase I Budget Reflects Learning from Previous Project



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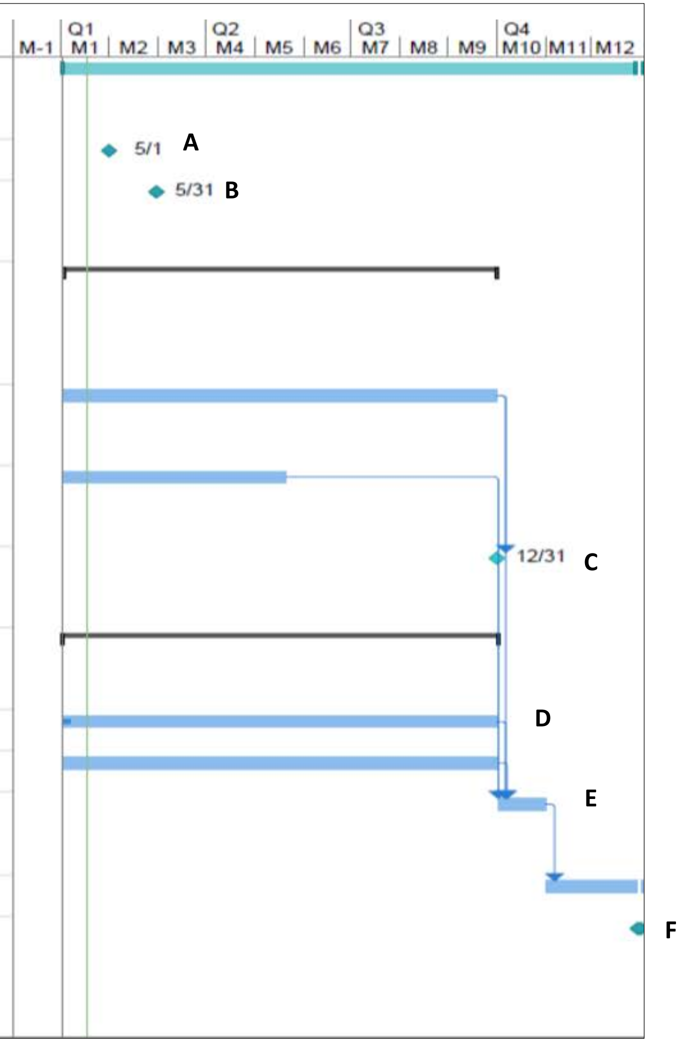
Project Timeline and Milestones

Task Name	Start	Finish	Task Level Cost
Task 1.0 Project Management and Planning	**Mon 4/2/18**	**Fri 3/29/19**	$154,510
Project Management Plan Updated	Tue 5/1/18	Tue 5/1/18	
Presentation to NETL Federal Project Manager at Kick-off Meeting	Thu 5/31/18	Thu 5/31/18	
Task 2.0 Preliminary Design and Site Engineering Analysis for 10 Mwe Capture Unit	Tue 4/3/18	Mon 12/31/18	$505,174
Subtask 2.1 Analysis for 10 MWe at new potential host site	Tue 4/3/18	Mon 12/31/18	
Subtask 2.2 Analysis for 10 Mwe at potential host site: Abbott	Tue 4/3/18	Mon 8/20/18	
Design and Engineering Site Analysis Complete	Mon 12/31/18	Mon 12/31/18	
Task 3.0 Environmental Health & Safety (EH&S) and Permitting Analysis	Mon 4/2/18	Tue 1/1/19	$91,273
Subtask 3.1 Identify NEPA contractor	Mon 4/2/18	Mon 12/31/18	
Subtask 3.2 EH&S Analysis	Tue 4/3/18	Tue 1/1/19	
Task 4.0 Selection of Host Site and Commitment	Wed 1/2/19	Thu 1/31/19	$85,884
Task 5.0 Phase I Reporting	Fri 2/1/19	Fri 3/29/19	$62,903
Topical Report submitted and final project briefing to NETL Federal Project Manager	*Sun 3/31/19*	*Sun 3/31/19*	



Milestone Log

Project on track

Budget Period	ID	Task Num ber	Description	Planned Completion Date	Actual Completion Date	Verification Method
1	A	1	Updated Project Management Plan	5/1/2018	4/20/2018	Project Management Plan file
1	B	1	Kickoff Meeting	5/31/2018	5/10/2018	Presentation file
1	C	2	Design and Engineering Site Analysis Complete	12/31/2018		Quarterly RPPR file
1	D	3	NEPA Contractor Selection	12/31/2018		Quarterly RPPR file
1	E	4	Host Site Selection and Commitment	1/31/2019		Quarterly RPPR file
1	F	5	Phase 1 Topical Report Completed	3/31/2019		Topical Report File
1	QR	1	Quarterly RPPR report	Each quarter		RPPR files

Risk Analysis and Mitigation

Description of Risk	Probability	Impact	Risk Management Mitigation and Response Strategies
Technical Risks			
Scale-up risk: Vapor and liquid mal-distribution in the absorber column	Low	Medium-High	• Leverage Linde experience in designing other large columns • Model distribution of fluids in the column
Solvent-related issues (corrosion, adequate supply, handling)	Medium	Medium-High	• BASF expertise and testing experience from 0.5 and 1.5 MWe pilot plants • BASF confirmation of solvent supply • Use data from corrosion coupon testing from pilot plants
Unknown contaminants in the flue gas and amine carry-over	Medium	Medium	• Leverage 0.5 and 1.5 MWe pilot plants • Confirm dry bed configuration for emissions control at large scale • Measurement of particulates density and nano-scale size distribution in the flue gas stream to determine impact of aerosol and to provide for mitigation • Detailed analysis (including heavy metals) of flue gas and liquid streams
Integration with operations at the selected host site	Low	Medium	• Phase 1: evaluate any potential risks and mitigated through understanding of host site operating regime • Host site operating characteristics incorporated into design, control logic, and operations of PCC large pilot.
Wastewater stream management	Low	Medium	• Evaluate options for wastewater management that allow recycle and reuse • Evaluate treatment options for make-up water that remove contaminants and reduce discharge volume.
Testing of new process units for energy optimization	Medium	Medium	• Leverage overall team expertise • Leverage external partners know-how

Risk Analysis and Mitigation

Description of Risk	Probability	Impact	Risk Management Mitigation and Response Strategies
Management risks			
Uncertainty of time required for obtaining environmental permits	Medium	High	• Based on previous projects and interactions with Illinois EPA typical timelines are well understood. • One of the potential sites (CWLP) produces water and will probably issue the required permit.
Uncertainty of time required for NEPA documentation especially if an Environmental Impact Statement (EIS) is determined to be required	Low	High	• Past experience has shown that EIS is not likely. NEPA documentation will be reviewed and input gathered early.
Project cost overruns	Medium	High	• This is more of an issue for Phase III, but will be addressed through clear scope definition, proper supplier/vendor selection and completion of full engineering prior to procurement.
Negative Stakeholder response	Medium	Medium	• Early communication initiated with stakeholders and feedback incorporated into the selection of the host site and the actual plot plan for the large pilot. Stakeholders informed of project benefits and value.

Risk Analysis and Mitigation

Description of Risk	Probability	Impact	Risk Management Mitigation and Response Strategies
Resource Risks			
Flue gas and utilities non-availability from power plant	Low	High	• Availability of required utilities will be confirmed with the host site and will be a key attribute used in the selection of the host site for the large pilot. • PCC large pilot design and control will include flexibility to handle variations in flue gas quantity and quality (e.g., CO_2 and O_2 concentrations).
Unavailability of operators and key individuals with past experience and know-how	Low	Medium	• Commitment from all participants to make project successful • Continue to ensure commitment during project execution

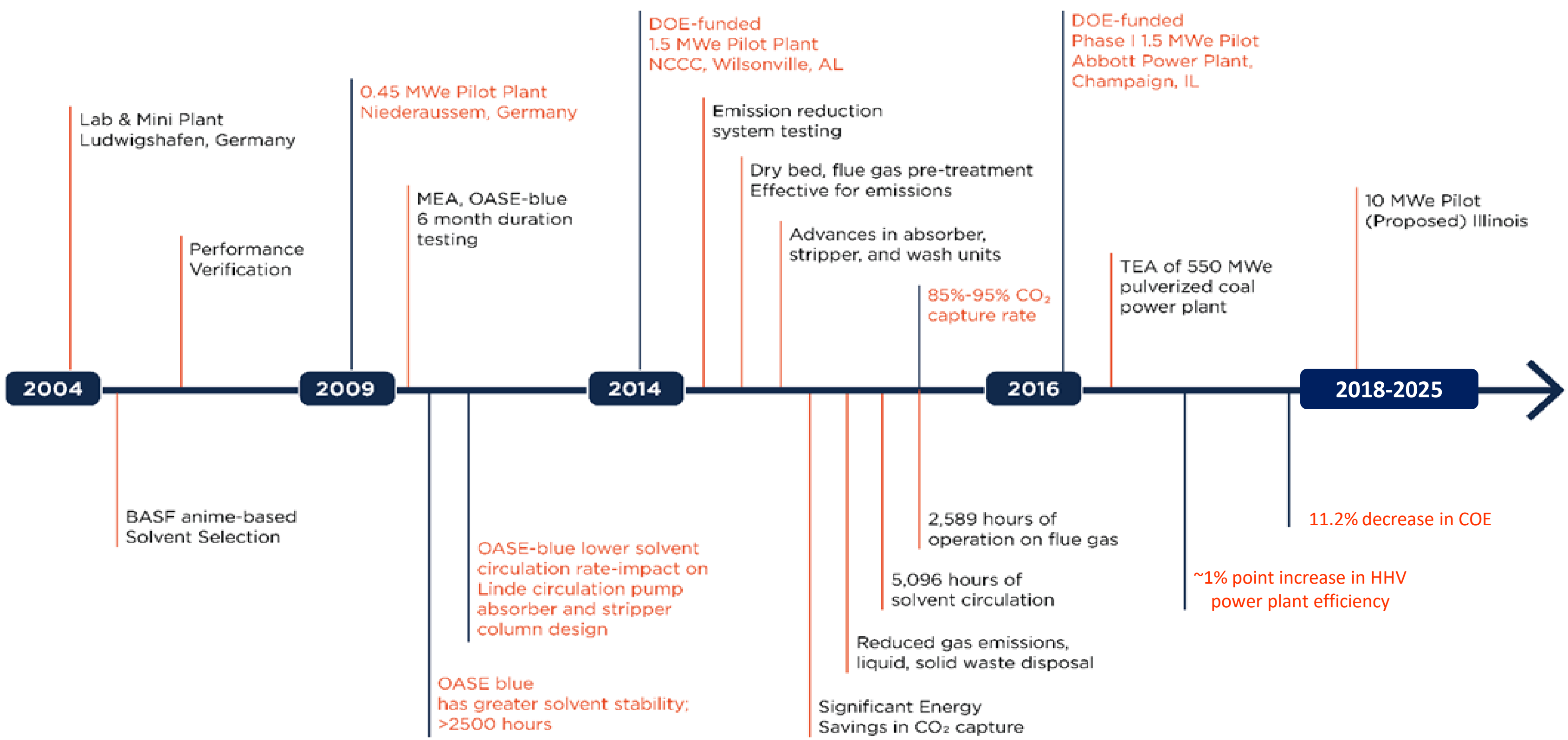
Phase I Deliverables

Task / Subtask	Deliverable Title	Anticipated Delivery Date
1.0	Project Management Plan	Update due 30 days after award. Revisions to the PMP shall be submitted as requested by the Project Officer.
5.0	Phase I Topical Report	March 31, 2019

OVERVIEW OF TECHNOLOGY DEVELOPMENT

Development Timeline for Technology

Consistent investment in technology maturation



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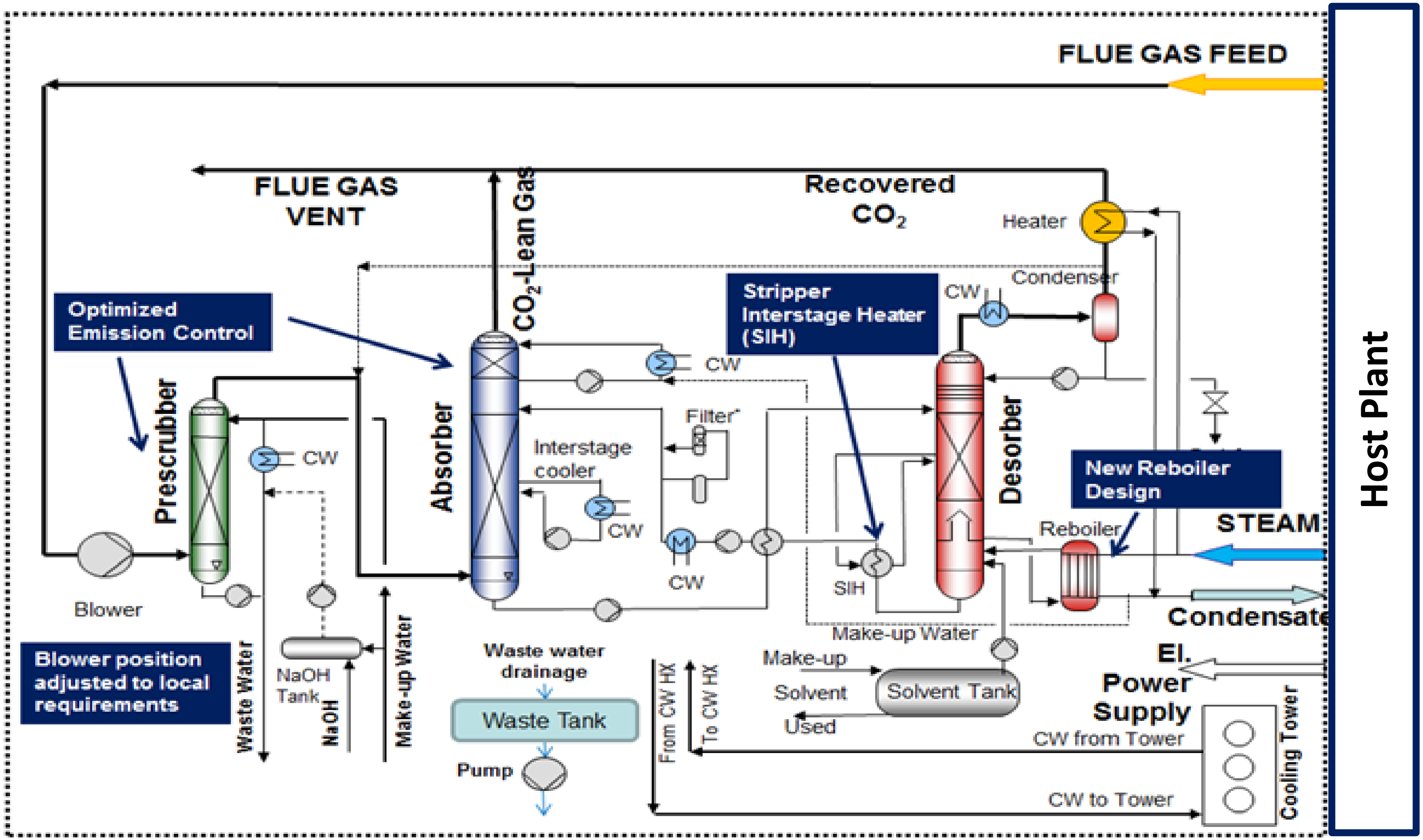
Technology performance to date

PP1= Niederaussem; PP2=NCCC

Test/Performance Attribute	PCC Pilot Plant	Key results and current achievement against targets	Remarks
Solvent selection	PP1	Two solvents screened following benchmark testing with MEA. OASE® blue selected	Solvent selected to optimize performance, emissions, and cost
CO_2 capture rate	PP1, PP2	Recovery > 90% as per target	Achieved
CO_2 purity	PP1, PP2	Purity > 99.9% (dry basis) as per target	Achieved
Plant capacity	PP1, PP2	• PP1: 7.2 tonnes CO_2/day (0.45 MWe) • PP2: >25 tonnes CO_2/day (>1.5 MWe per design target, >15,500 lb/hr flue gas)	Achieved. Higher capacity testing performed at PP2 – 10 days in May-June 2015. An additional week of higher capacity testing was conducted in Nov. 2015.
Regenerator steam consumption	PP1, PP2	~ 2.8 GJ/tonne-CO_2 (Intrinsic energy requirement)	Achieved (20% lower than MEA). ~ 2.7 GJ/tonne-CO_2 observed in PP2
Cyclic capacity	PP1, PP2	>20% compared to MEA	Achieved
Emissions control testing	PP1, PP2	Identified and validated BASF/RWE patented dry bed configuration of water wash unit to reduce emissions as per design target. Aerosol control configuration in flue gas stream tested and evaluated	Incorporated in PP2 design. Detailed isokinetic measurements (flue gas & treated gas) performed to confirm effectiveness of emissions control options (such as dry bed configuration) for high aerosol content flue gas, in particular flue gas with a high nanoparticle size particle density.
Regenerator operating pressure	PP2	Pressure up to 3.4 Bara	Achieved & confirmed benefits for compressed CO_2 production. Pressure parametric testing completed in Nov. 2015. Long-duration testing was performed at 3.4 bara.
Materials of construction	PP1	Wide range of materials (CS, SS, concrete with PP inliner, FRP, etc) tested in sections and in coupons	Enabled optimized material specifications for PP2 and for commercial cases
Validation of unique process features	PP1, PP2	• High capacity packing in the absorber column • Blower downstream of absorber (PP2) • Unique two-phase flow reboiler design (PP2) • Gravity-driven interstage cooler (PP2)	Design improvements for reducing the energy required for solvent regeneration through heat integration were identified. Stripper inter-stage heater (SIH) design can result in ~2.3 GJ/tonne CO_2.
Long-term testing for solvent stability assessment	PP1, PP2	• PP1: >26,000 hrs (>3 years) of testing • PP2: ~ 1,500 hrs of continuous testing under steady state conditions	• PP1: Achieved • PP2: Long term testing successfully completed from May through July 2016.

Overview of Capture System for Large Pilot Plant

Technology features in large pilot design



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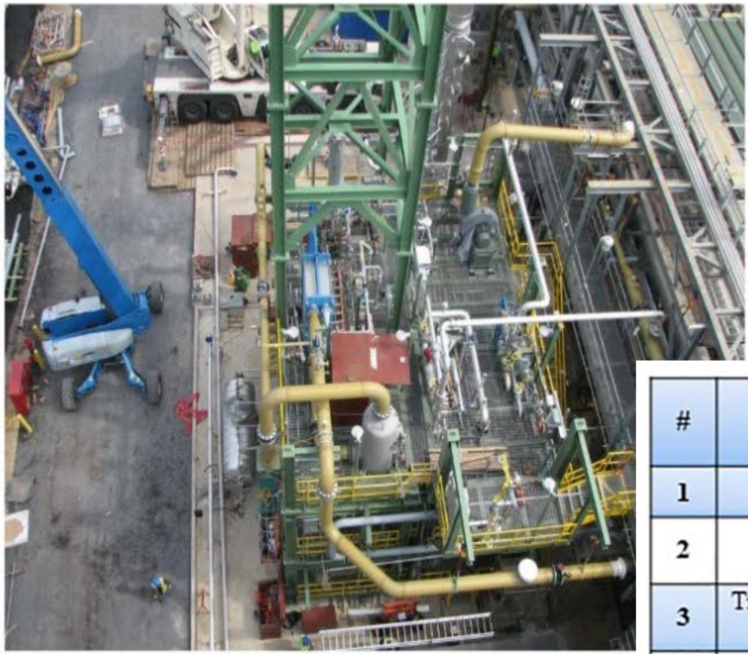
Wilsonville PCC Pilot Plant

Project essentials

- DOE-NETL funded project ($16.2 million funding)
- Total project cost $22.7 million
- Location: 880 MWe Gaston Power plant (operated by Southern Co.) in Wilsonville, AL
- Site of the National Carbon Capture Center
- Capacity: Up to 6,250 Nm^3/h flue gas from coal fired power plant (30 t/d CO_2); Up to 1.5 MWe
- CO_2 purity 99+ vol % (Dry basis)
- Project start: November 2011
- Start-up: January 2015
- Project Duration: 4.5 years
- Partners: Linde LLC, Linde Engineering North America, Linde Engineering Dresden, BASF, DOE-NETL, EPRI, Southern Company (Host site)

Testing at NCCC

Parametric testing performed for 1.5 MWe pilot plant



#	Key variable	Status
1	Flue gas flow rate	7,500 to 15,750 lbs/hr
2	Flue gas temperature to absorber	86° F to 104° F
3	Treated gas temperature exit absorber	86° F to 115° F
4	Lean solution temperature to absorber	104° F to 140° F
5	Inter-stage cooler	On (104° F) / Off
6	Regeneration pressure	1.6 to 3.4 bars
7	Solvent circulation rate	Varied from 80 to 120%
8	CO_2 capture rate	• 90% typical • Varied from 85% to >95%

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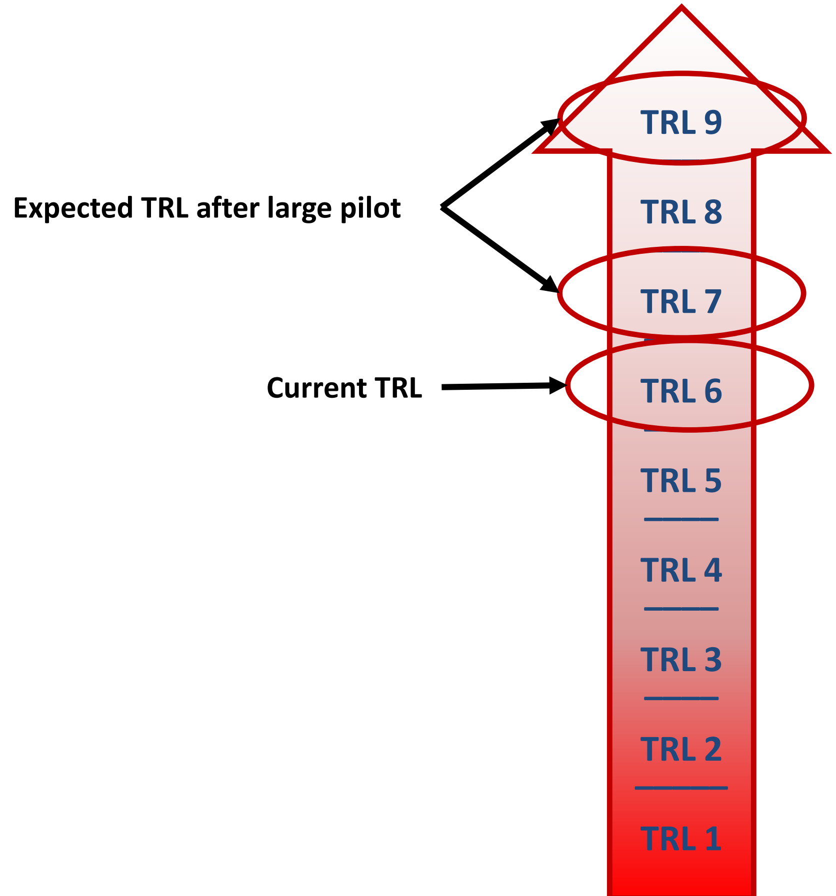
Technology Gap Analysis

TRL improvements that would result from large scale pilot

CO_2 Capture Plant Subsystems
Absorber and Stripper Columns[1]
Heat exchangers and reboiler
Stripper heat integration and recovery
Materials of construction
Emission control
Solvent Management



1. Columns expected to achieve TRL 9 based on Linde related experience in building up to ~ 12 m diameter columns for other commercial applications.

Technology Gap Analysis

Path forward defined to close all technology gaps in large pilot

Technology Gap	Description/Comments	Path Forward
Absorber column scale-up	• Uniform vapor and liquid distribution. • Affordable construction strategy	• Apply Linde commercial experience • Assess modular shop fabrication vs field installation. Implement low cost column construction strategy
Flue gas concentration variability	• Variability in flue gas composition (CO_2, O_2, SO_2, etc.)	• Recycle CO_2 from stripper to flue gas (FG) and design direct contact cooler to manage higher SO_2 concentration in FG.
Load following strategy and response	• Varying loads based on University power and heat demand	• Implement a device-appropriate load-following strategy for the capture plant
FG impurities leading to solvent losses	• Significant aerosol formation in the flue gas may increase amine carryover	• Measure and characterize aerosols in flue gas and make provisions for mitigation
Regeneration energy optimization	• An advanced stripper configuration required to minimize regeneration energy	• Reduce reboiler duty by incorporating stripper inter-stage heating
Solvent Management	• Large quantities of solvent present challenges around delivery logistics, storage, and disposal	• Develop solvent management options using BASF's experience • Test portable solvent reclaiming system if necessary
Water and Wastewater Management	• Large amounts of wastewater with trace amounts of contaminants may incur high permitting costs or reach capacity limits	• Evaluate options for treatment or reuse of wastewater

Process Performance and Cost Summary 550 MWe

Based on 1.5 MWe pilot test and Aspen Plus simulation results

Parameter	DOE-NETL Case B12A	DDE-NETL CASE B12B	Linde-BASF LB1	Linde-BASF SIH
Scenario	No O_2 capture	90% CO_2 Capture with Cansolv PCC process	90% CO_2 Capture with OASE° blue	90% CO_2 Capture with OASE° blue and SIH
Net power output (MWe)	550.0	550.0	550.0	550.0
Gross power output (MWe)	580.0	642.0	630.4	629.3
Coal flow rate (tonne/hr)	179.2	224.8	221.9	218.5
Net HHV plant efficiency (%)	40.70%	32.50%	32.88%	33.40%
Total overnight cost ($2011) ($/MM)	$1,379	$2,384	$1,970	$1,950
Cost of CO_2 captured with T&S ($/MT)	N/A	$69.01	$54.58	$53.72
Cost of CO_2 captured without T&S ($/MT)	N/A	$58.00	$43.58	$42.71
COE ($/MWh) with T&S	$82.30	$142.80	$127.97	$126.50

LB1 - Linde-BASF PCC plant incorporating BASF's OASE® blue aqueous amine-based solvent

SIH - New Linde-BASF PCC plant incorporating the same BASF OASE® blue solvent featuring an advanced stripper inter-stage heater design

ENVIRONMENTAL, HEALTH AND SAFETY ANALYSIS

Potentially Hazardous Materials

Engineering controls and/or safeguards in place to limit possible consequences

	Safeguards
1)	• Bulk heat stable salts removal options • Anti-foaming and anti-corrosion agents available, if needed
2)	• Module shelters to redirect rain water • Impermeable pads under modules and columns • Sloped floor - drainage to a sump
3)	• Water reuse/recycle considered • Neutralization of waste water before disposal, if needed
4)	• Caustic tank surrounded by 6’ wall
5)	• Relatively small volumes of solvent • Solvent handling guidance from BASF
6)	• Emission Control System, including patented “dry bed” configuration • Treated gas vented at 170’
7)	• Storage tank surrounded by 3’ wall • Amine lines welded to prevent leakages

Probability of Occurrence						
	5 Very High					
	4 High					
	3 Medium		• Accumulated heat stable salts ①		• Carryover of amines ⑥	
	2 Low		• Surface runoff to ground ②	• Disposal of process condensate from DCC ③		
	1 Very Low			• Improper handling of caustic ④ • Improper handling of solvent ⑤	• Loss of containment ⑦	
Probability Impact Grid		1 Very Low	2 Low	3 Medium	4 High	5 Very High
		Impact of Risk				

Key Environmental Health & Safety Risks

Risk mitigation factors identified for design, build and operate activities

Safety and Health Risk	Mitigation Approach
Plant operations safety	• Applied Linde's comprehensive "Safety by Design" guidelines • Safety and operator training
Safety issues arising from improper design and operations/maintenance requirements not identified at design	• Implementation of Linde Gas Standard Requirements • Comprehensive Hazard and Operability study (HAZOP) • Comprehensive Process Safety Reviews (PSR)
Process operations safety	• Safety instrumented systems • Flow restriction and safety interlocks • Automatic safe shutdown capability incorporated in the large pilot plant design • Emergency power supply
Chemical exposure	• Multiple eye wash and emergency showers • Safe locations of vents and blow down • Proper sizing of relief valve and similar devices • Catch pots for capturing any leaks during maintenance
Solvent handling	• Rigorous operating procedures including mandatory usage of Personal Protection Equipment (PPE)
Solvent storage (regulatory requirements)	• OSHA and EPA regulated chemicals with threshold storage volume for process safety management checked. Confirmed solvent is not part of the classified chemicals list with threshold volume.

INTEGRATION WITH HOST SITE

Selecting the Host Site

Site Selection Criteria	
Technical	Flue gas availability
	Flue gas CO_2 concentration
	Aerosol concentration in flue gas
	Steam and utility availability for ISBL
	Design costs for OSBL
	Available plot size for ISBL
	Use of domestic coal
	Existing abatement equipment (FGD, ESP, SCR, etc.)
	Logistics of transportation and lifting
Regulatory and Environmental	Permitting requirements
	Permitting timelines
	Supports NEPA
	Safety culture
Financial and Business Agreements	Cost share commitment
	Contractual terms and conditions
	Site interest
	Sign-off requirements
	Potential for capture system to permanently remain
	Interest in serving as future training site
	Personnel support and responsiveness

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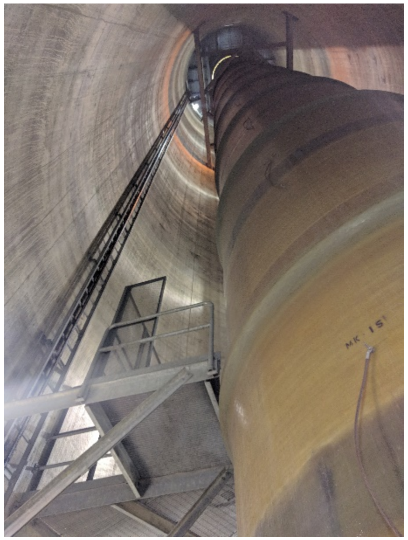
Host Site PP-1

Water and power supplier

Imagery ©2018 Google, Map data ©2018 Google 100 ft

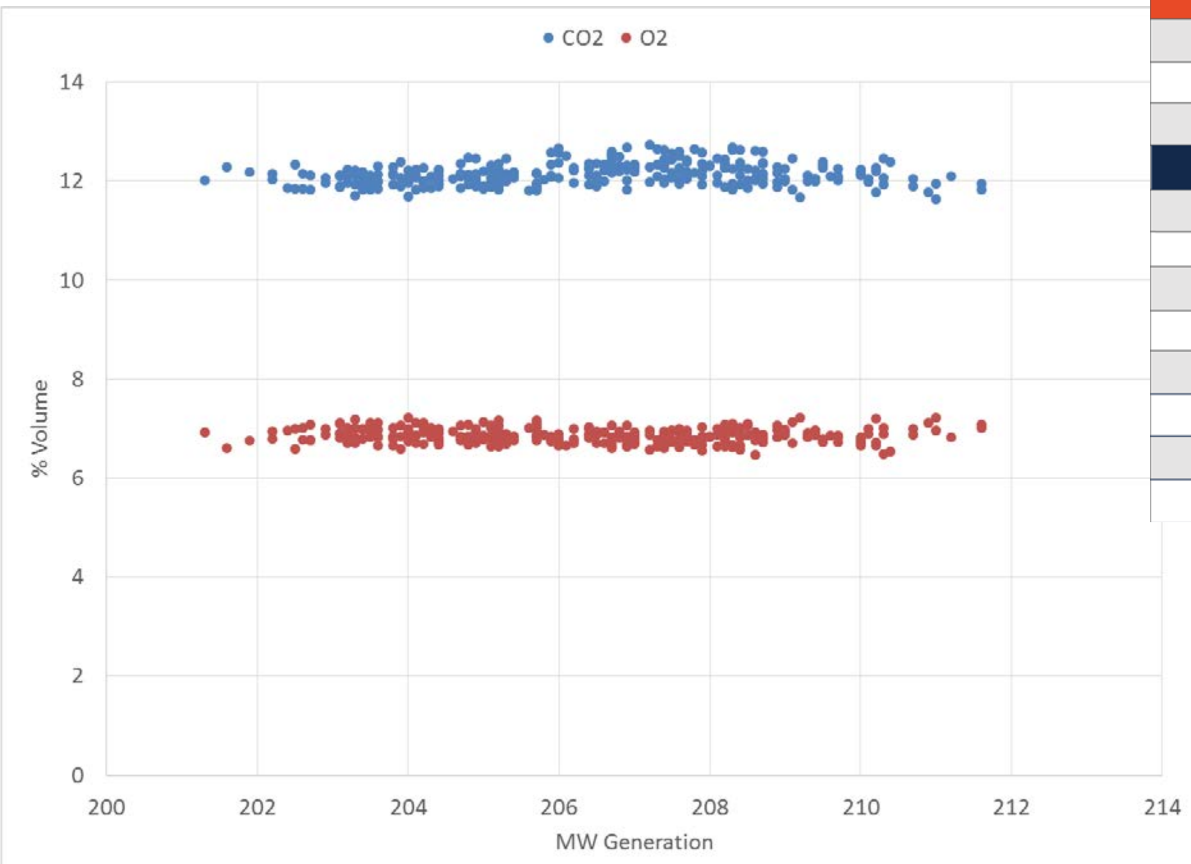
OSBL Challenge at PP-1

Stack Gas Measurements at PP-1



Stack Gas Measurements at PP-1

Values compare well to traditional PC plant



Item	Unit	Value
Temperature	°F	200
Pressure (gauge)	inch-Hg	0.2
Flow rate	acfm	675.985
Gas compision		
Moisture	vol %	16.3
CO_2	vol % (dry)	12.8
O_2	vol % (dry)	6.4
SO_2	ppmv (dry)	31.3
NO_x	ppmv (dry)	23.0
HCL	ppbv (dry)	122
Hg	lb/hr	0.000336
Particulate	lb/hr	2.587

Host Site PP-2

- Three coal-based boilers; four natural gas
- **Separate treatment system for each fuel**
- Testing will run two coal boilers (IL high-sulfur coal)
- Electrostatic precipitators and a wet Flue Gas Desulfurizer (FGD) in place
- **Tradition of evaluating and showcasing new emission technologies**

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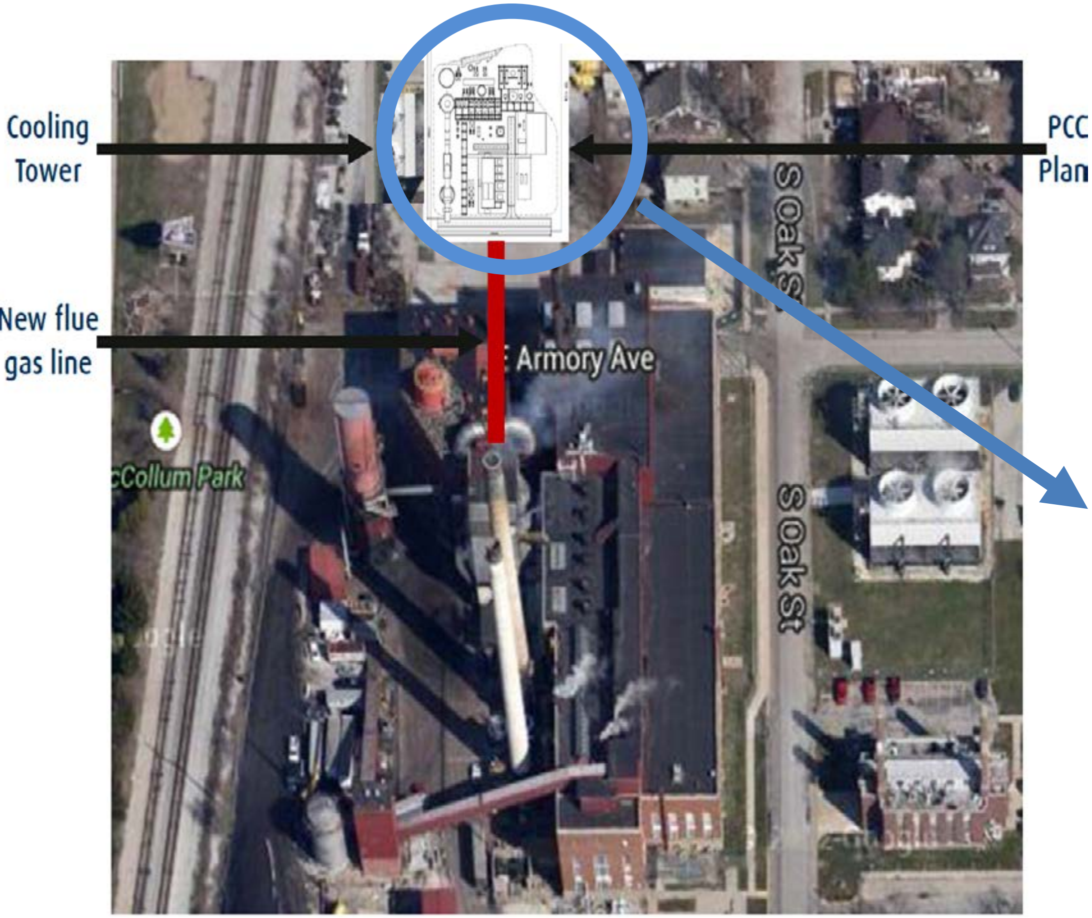
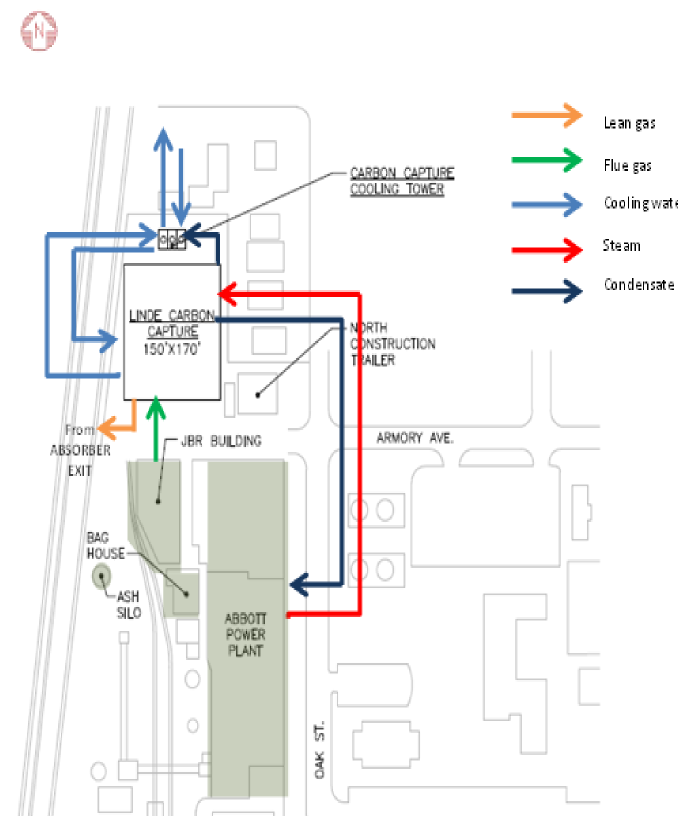
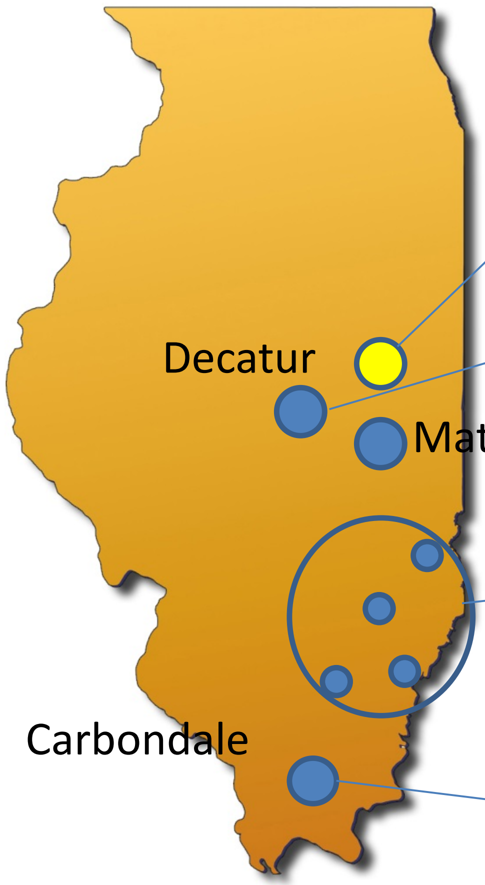
PP-2 Carbon Capture Plant Site Evaluated





Regional & Global Test Bed for CCUS

Concentration of natural resources and intellectual capital



Fairfield, Olney, Robinson, Mt. Carmel

- Capture of CO_2 : PP-1 or PP-2

ADM MGSC Richland COMMUNITY COLLEGE

- Storage of CO_2 : ADM Project

MATTOON
MATTOON, ILLINOIS: Working Together to Build the Future

- Utilization of CO_2 : Enhanced Oil Recovery (EOR)

Illinois Eastern Community Colleges

- Operator Training

Southern Illinois University Carbondale

- Coal combustion

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