LARGE PILOT SCALE TESTING OF LINDE/BASF POST-COMBUSTION CO_2 CAPTURE TECHNOLOGY AT THE ABBOTT COAL-FIRED POWER PLANT

DOE/NETL Funding Award DE-FE0026588

Phase I Close-out Meeting

November 17, 2017

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PROJECT MANAGEMENT AND PARTICIPANTS

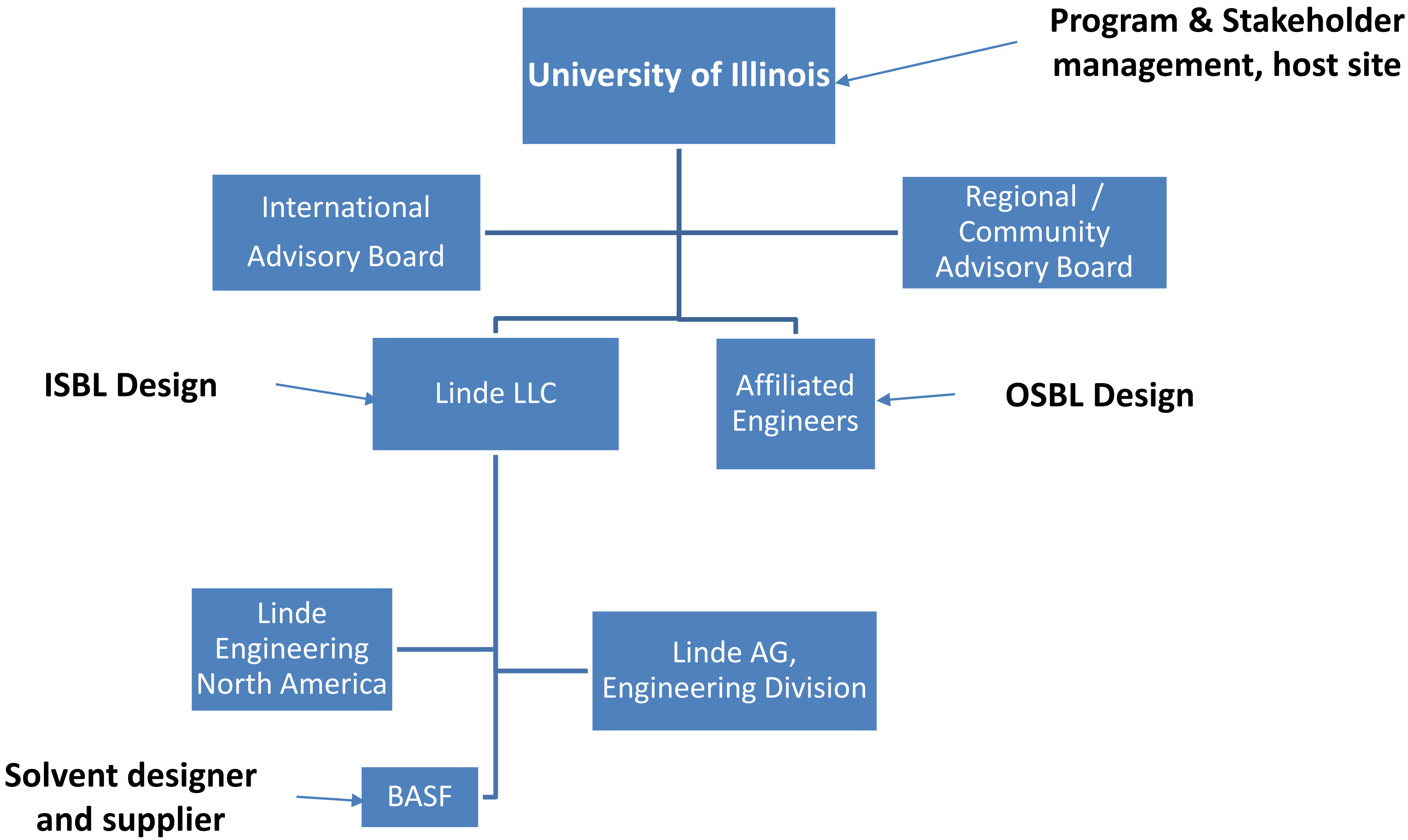
Objectives for Phase 1

All have been met

- Defining the project in detail
- Formulating a project management plan
- Developing a preliminary plant design to enable cost estimates within ± 20%
- Obtaining a host site agreement and other financial commitments to prepare a detailed Phase 2 application

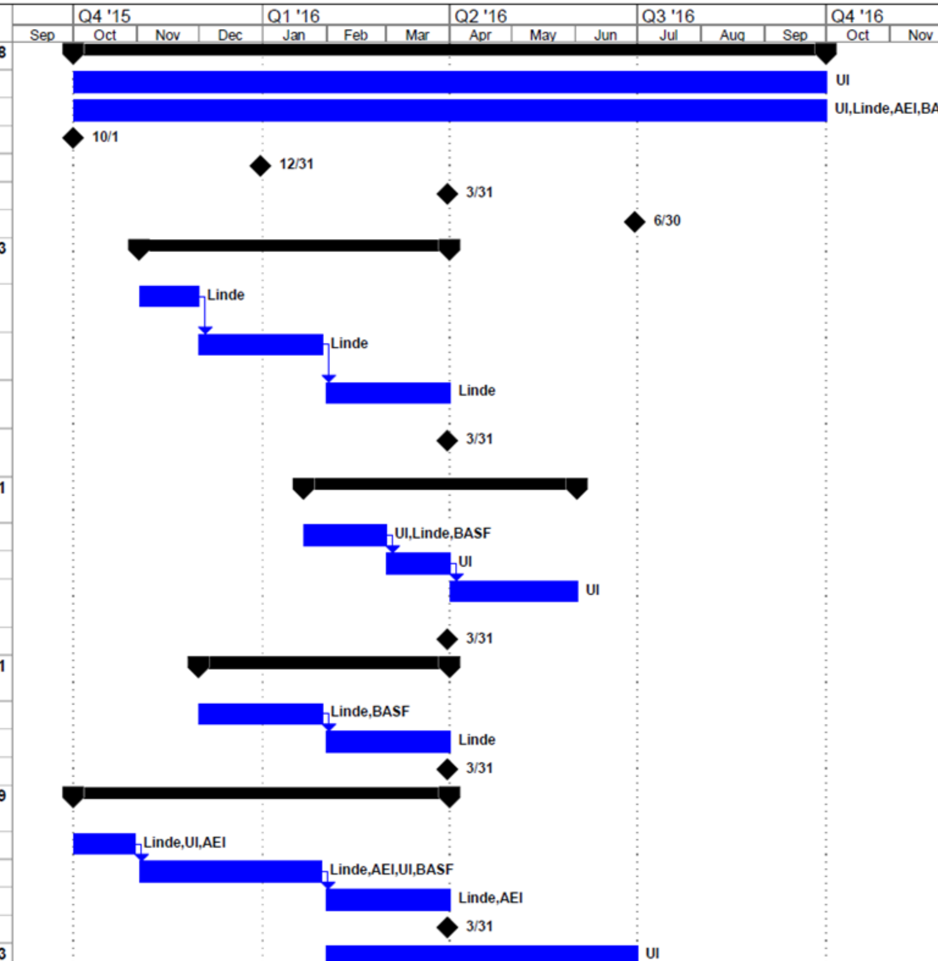
Phase 1 Team

Well defined roles based on relevant capabilities



Project Timeline and Milestones

Task Name	Start	Finish	Cost
Task 1.0 - Project Management and Planning	10/1/15	9/30/16	**$170,588**
Subtask 1.1 - Monitoring and Control	10/1/15	9/30/16	
Subtask 1.2 -Briefings, Reports and Conferences	10/1/15	9/30/16	
Updated Project Management Plan	10/1/15	10/1/15	
Project Kickoff Meeting	12/31/15	12/31/15	
Continuation Application Submission	3/31/16	3/31/16	
Executed Agreements	6/30/16	6/30/16	
Task 2.0 - Technology Engineering Design and Economic Analysis	11/2/15	3/31/16	**$276,413**
Subtask 2.1 - Basis and Scope for the Power Plant with CO2 Capture	11/2/15	11/30/15	
Subtask 2.2 - Detailed Design of the Power Plant with Post-Combustion Capture	12/1/15	1/29/16	
Subtask 2.3 - Economic Analysis of the Power Plant with CO2 Capture and Compression	2/1/16	3/31/16	
Technology Engineering Design and Economic Analysis Report Submission	3/31/16	3/31/16	
Task 3.0 - Environmental, health and safety (EH&S) Risk Assessment	1/21/16	6/1/16	**$176,051**
Subtask 3.1 - Preliminary EH&S Analysis	1/21/16	2/29/16	
Subtask 3.2 - Phase II Environmental Questionnai	3/1/16	3/31/16	
Subtask 3.3 - Determine environmental permitting requirements and prepare documentation	4/1/16	6/1/16	
EH&S Study Report Submission	3/31/16	3/31/16	
Task 4.0 - Technology Gap Analysis and Risk Management	12/1/15	3/31/16	**$107,401**
Subtask 4.1 - Technology Gap Identification	12/1/15	1/29/16	
Subtask 4.2 - Risk Mitigation Planning	2/1/16	3/31/16	
Technology Gap Analysis Submission	3/31/16	3/31/16	
Task 5.0 - Design, Engineering and Costing of the Large Pilot Plant	10/1/15	3/31/16	**$481,609**
Subtask 5.1 - Design Basis Definition	10/1/15	10/30/15	
Subtask 5.2 - Large Pilot Plant Design and Engine	11/2/15	1/29/16	
Subtask 5.3 - Large Pilot Plant Costing	2/1/16	3/31/16	
Phase I Topical Report Submission	3/31/16	3/31/16	
Task 6.0 - Phase II Application Preparation	2/1/16	6/30/16	**$90,023**



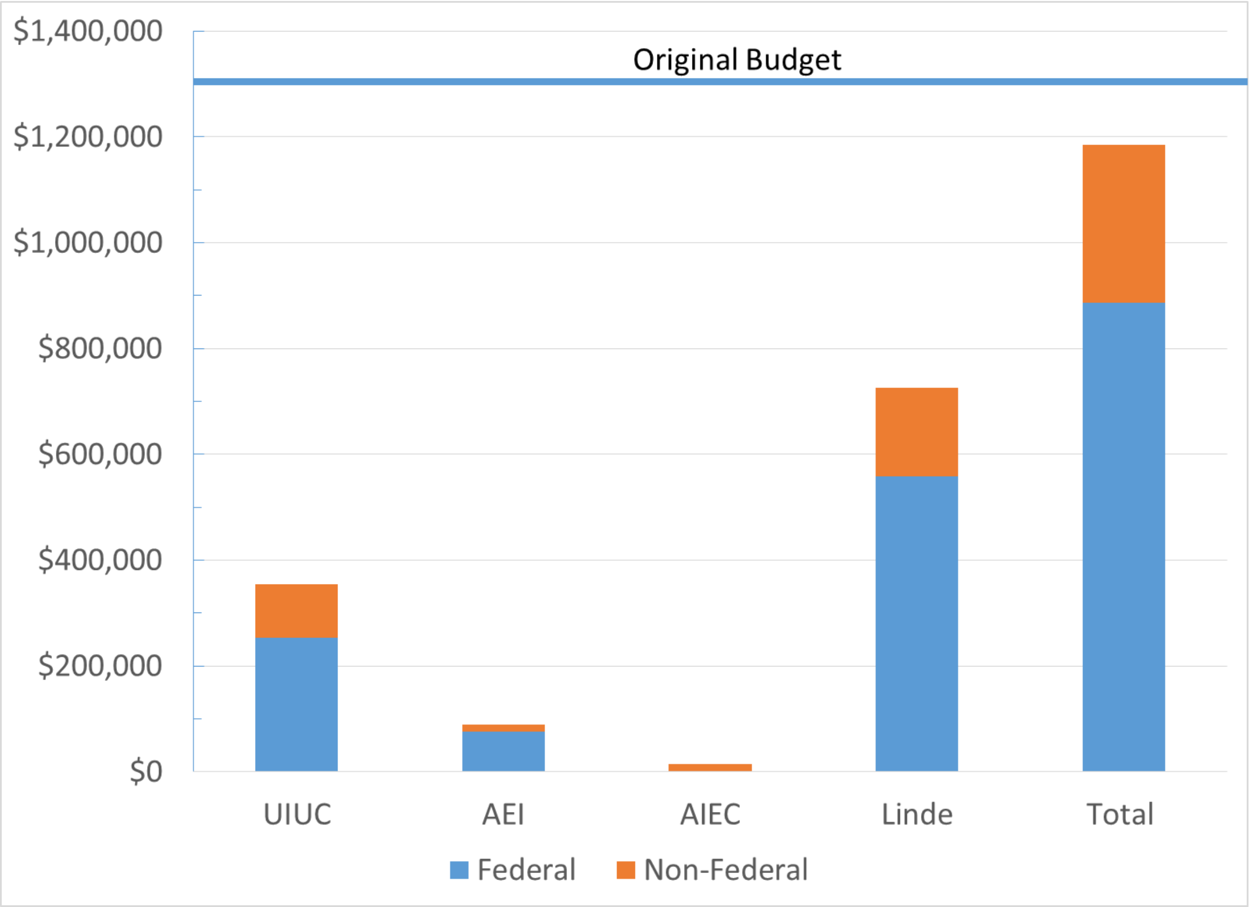
Project Milestones and Tasks

All completed on-time and within budget

Budget Period	Task / Subtask	Milestone Description	Planned Completion	Actual Completion	Verification Method	Status / Comments
1	1	Updated Project Management Plan	10/1/2015	10/1/2015	Project Management Plan File	Completed
1	1	Kick-off Meeting	12/30/2015	12/10/2015	Presentation File	Completed
1	2	TEA completed	3/31/2016	3/31/2016	Presentation File	Completed
1	3	EH&S Study Completed	3/31/2016	3/31/2016	Presentation File	Completed
1	5	Phase I Topical Report Completed	3/31/2016	3/31/2016	Presentation File	Completed
1	1	Host Site Agreement Completed	6/30/2016	6/25/2016	Signed Agreement	Completed

Phase I Funds

Under budget and exceeded cost share requirements



- Under original total budget of $1.3 MM
- Cost share of ~25%, exceeded 20% requirement

AIEC= Association of Illinois Electric Cooperatives

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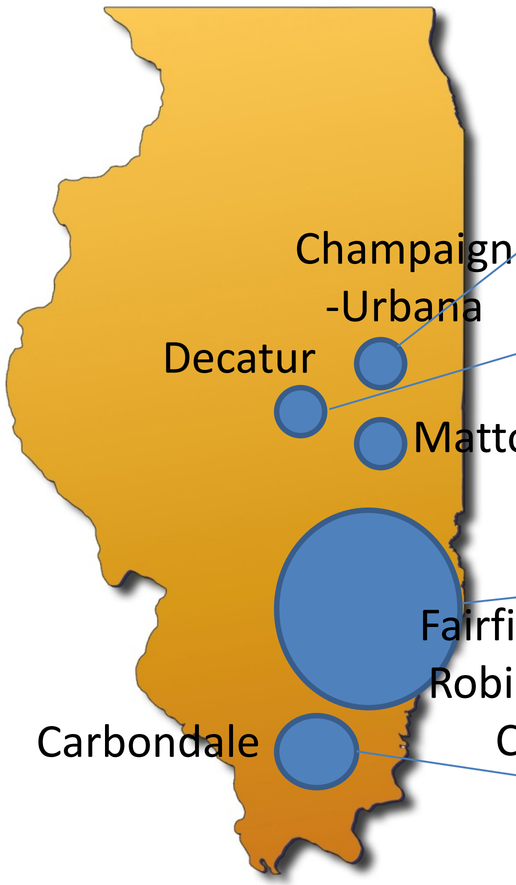
Key Personnel

Organization	Role	Key Personnel
University of Illinois	Host Site / Technology Evaluation	Dr. Kevin C OBrien Dr. Yongqi Lu
The Linde Group	Technology Developer, ISBL Engineering, Procurement, Construction	Dr. Krish Krishnamurthy Torsten Stoffregen Makini Byron
BASF	Technology Developer, basic design and solvent management	Dr. Sean Rigby
Affiliated Engineers	OSBL Engineering	David Guth, LEED AP

Regional & Global Test Bed for CCUS

Concentration of natural resources and intellectual capital

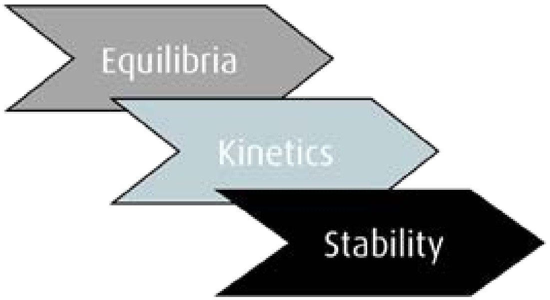


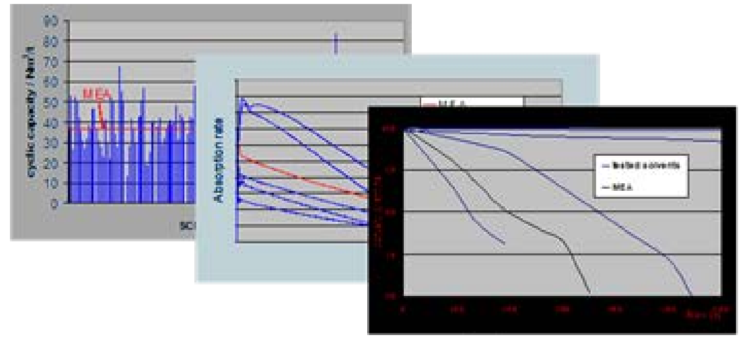
- Capture of CO_2 : Abbott Power Plant UIUC
- Storage of CO_2 : ADM Project
- Utilization of CO_2 : Enhanced Oil Recovery (EOR)
- Operator Training
- Coal combustion

OVERVIEW OF TECHNOLOGY DEVELOPMENT

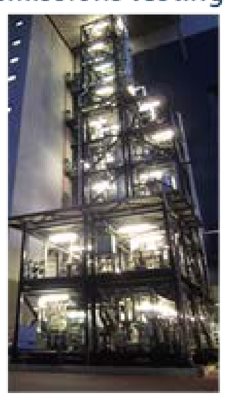
BASF OASE® blue technology development

Linde adopted and optimized for PCC applications





Lab. & Mini plant (2004)	Pilot: 0.45 MWe (2009)	Pilot: 1.5 MWe (2014)	Large Pilot (proposed): 15 MWe (2016-2020)
— Ludwigshafen, Germany — Solvent selection & performance verification	— Niederaussem, Germany — Process opt., materials & emissions testing	— Wilsonville, AL (NCCC) — Design improvements, emissions confirmation	— Abbott power plant, UIUC, Champaign, IL — Full value chain demo.



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.

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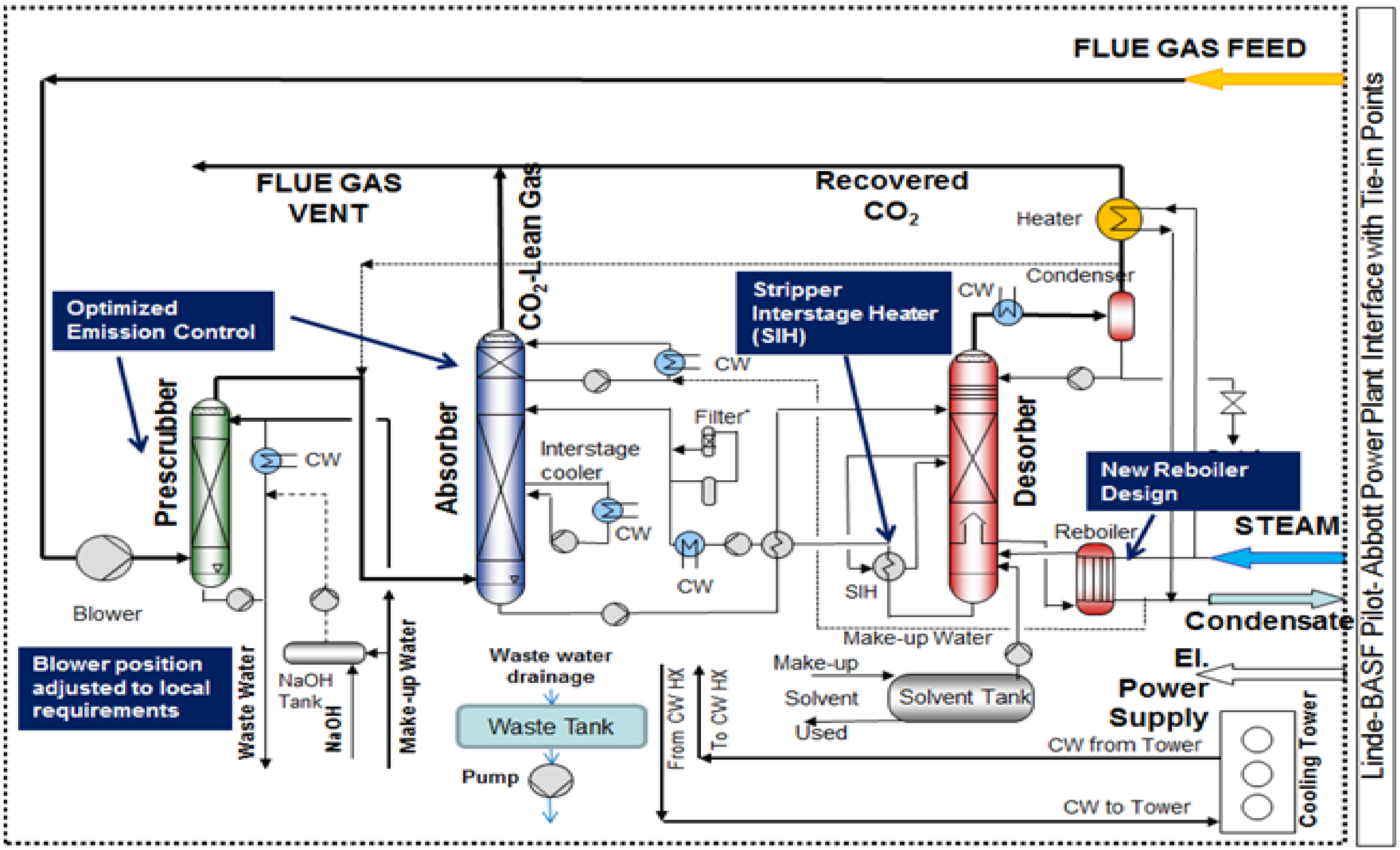
LARGE PILOT DESIGN AND TEST APPROACH

Overview of Capture System for Large Pilot Plant

Technology features in large pilot design



Preliminary CO_2 capture plant design basis

Large pilot captures 300 tons/day CO_2

CO_2 product:

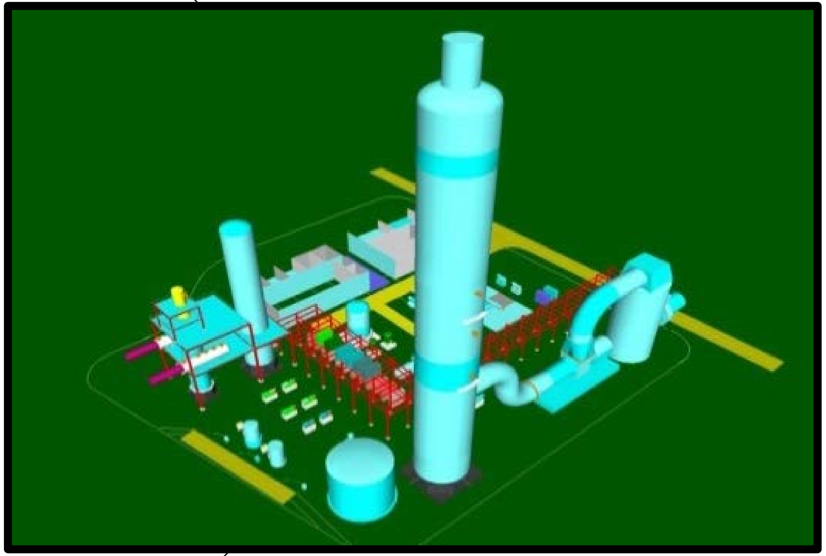
- 272 MTPD (300 tons/day)
- 90% capture efficiency
- 99.7+% purity (<100 ppmv O_2)
- ~1.2 bars delivery pressure at site boundary

Flue gas processed:

- Target capture plant capacity: 15 MWe
- Target flue gas flow rate: 77.6 tonnes/hr(wet)
- Flue gas composition (straight): CO_2 5.7mol%(wet)
  (with recycle): CO2 10.3 mol%(wet);

Operating requirements:

- Regenerator LP steam (3.4-4.8 barg): 17.0 tonnes/hr
- Electrical power: max 462 kW
- Cooling water: 132 gpm



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Test Cases Planned in Large Scale Pilot

Recycling important to increase level of CO_2

		Flue Gas Specification		Treated Gas	Total Captured CO_2
Description	**Unit**	Case 1 (Straight FG Flow)	Case 2/3 (FG w/ CO_2 recycle)	Case 2/3 (FG w/ CO_2 recycle)	Case 3 (CO_2 recycle at higher P)
Operating pressure	bar (psi)	1.0 (14.9)	1.0 (14.9)	1.0 (14.9)	3.4 (49.3)
Operating temperature	°F (°C)	200 (93.3)	200 (93.3)	104 (40)	104 (40)
Total Volumetric Flow	(Nm^3/h)	78,353	65,621	63,424	1,833
Total Mass Flow	lb/hr (kg/hr)	163,321 (74,081)	163,903 (74,345)	142,967 (64,849)	22,841 (10,361)
Composition:					
CO_2	mol%	5.7	10.4	1.1	97.7
N_2	mol%	68.8	72.7	78.7	0.0
Ar	mol%	0.8	0.9	0.9	0.0
O_2	mol%	10.3	10.9	11.8	0.0
H_2O	mol%	14.4	5.2	7.5	2.2
SO_2	ppmv	68.0 (max 200)	64.0	N/A	N/A
SO_3	ppmv	tbd	tbd	N/A	N/A
NO_x	ppmv	tbd	200	N/A	N/A
Chlorides	ppmv	tbd	tbd	N/A	N/A
Dust	lb/SCF	tbd	tbd	N/A	N/A

Case 1: Treat as-received flue gas: containing low concentration CO_2 (5.7%mol)

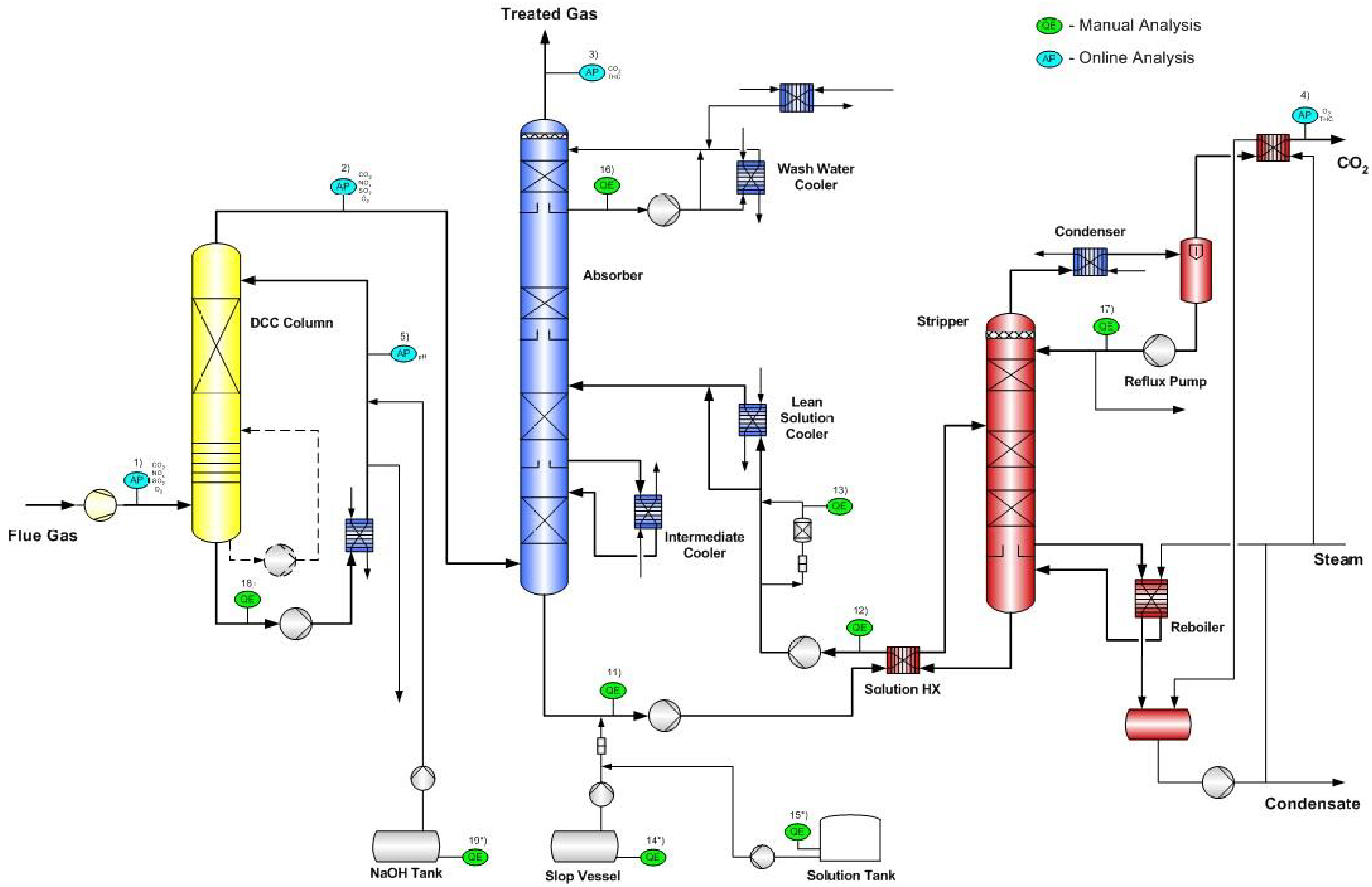
Case 2: Treat flue gas with CO_2 recycle: to increase the CO_2 concentration from 5.7%mol (without recycle) to 10.3%mol (with recycle).

Case 3: Treat flue gas with CO_2 recycle and stripping operation at a higher pressure

NB: 2016 measured CO2 concentration at Abbott (two coal boilers at full load) was 9.2% CO2 as opposed to 5.7% which was the design of the plant. This is more in line with the pulverized coal plants and recycle option in this case can increase the flue gas CO2 concentration to 13%, typical of PC boilers.

Large Pilot Analysis Points

Frequent analysis through online and manual sample points



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INTEGRATION WITH POWER PLANT

Host Site: Abbott Power Plant

Ideal site for large scale pilot testing of coal and natural gas

- Seven boilers total: three are coal based (Chain-grate stoker design) others natural gas
- **Coal side has completely separate treatment system from natural gas side**
- For testing will run two coal boilers
- Illinois high sulfur coal is burned
- Electrostatic precipitators and a wet Flue Gas Desulfurizer (FGD) in place
- **Tradition of evaluating new emission technologies**
- **Tradition of showcasing technologies to other power plants and education groups**

Major advantage that University owns and operates Host Site

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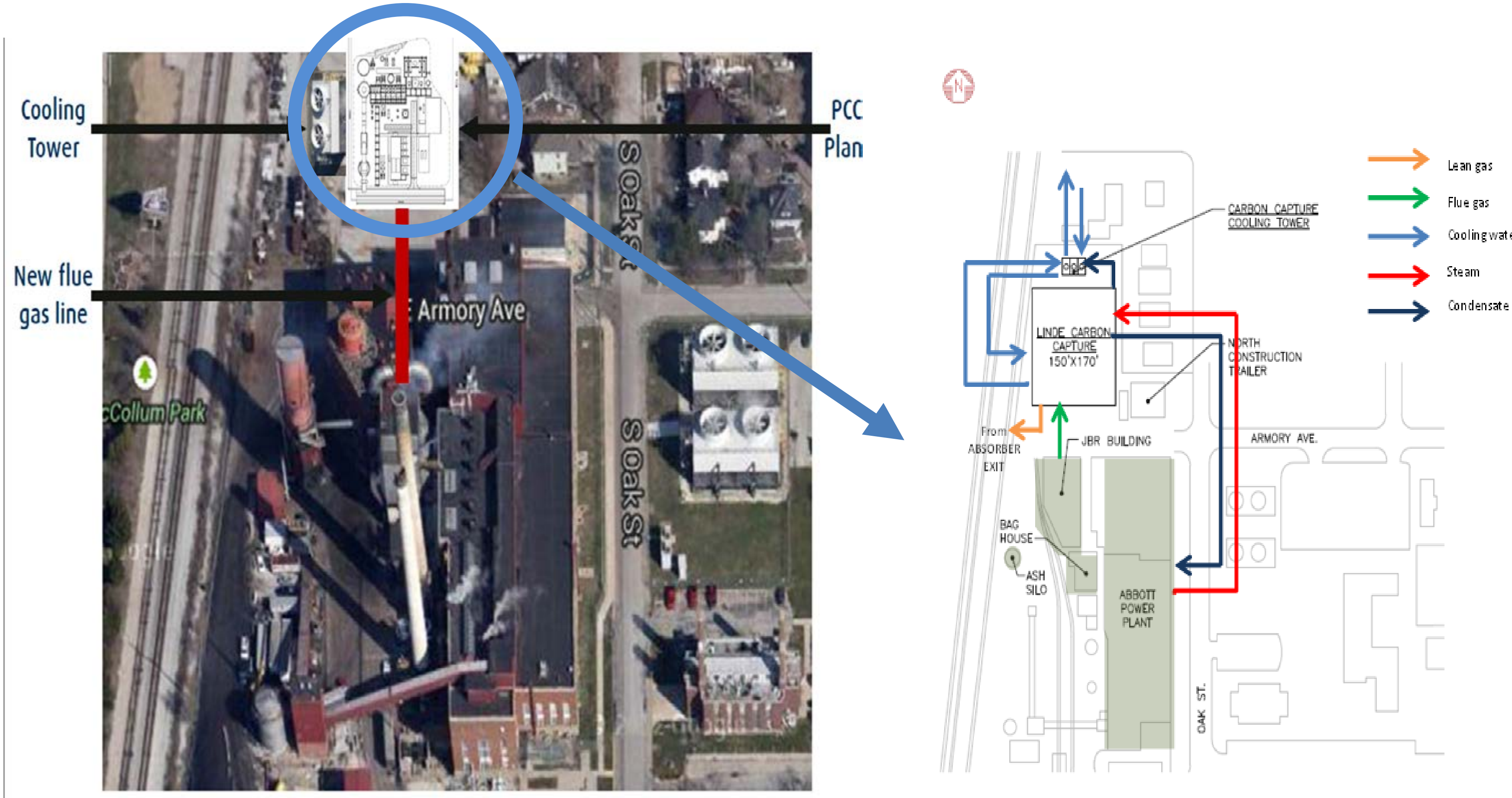
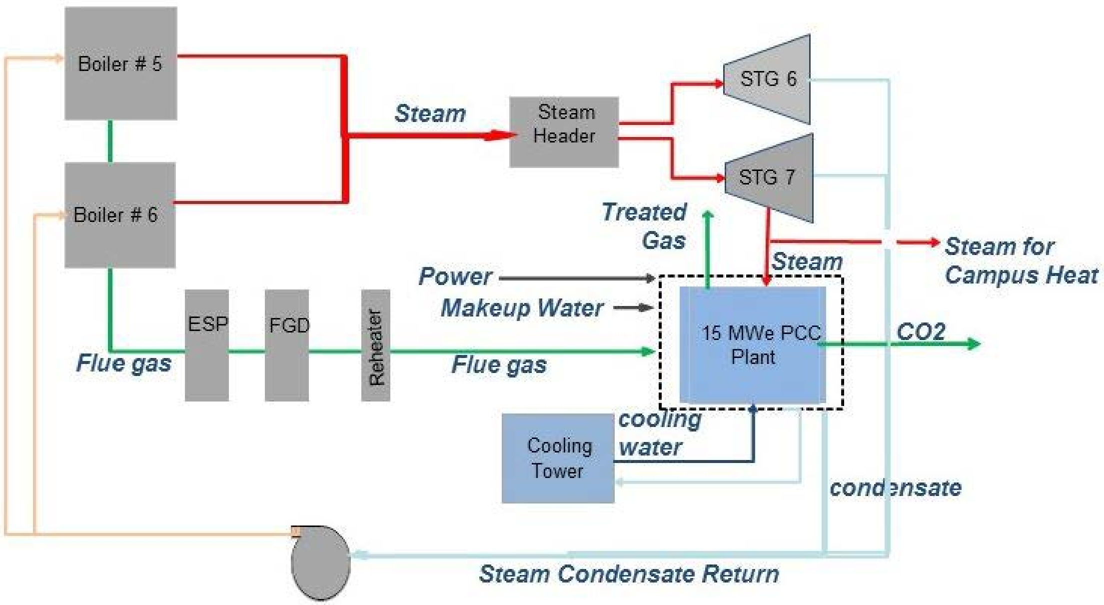
Site for Carbon Capture Plant Established and Evaluated

Located close to Abbott Power Plant



Extract flue gas POST CEMS Unit

Integration of Pilot Plant with Utilities at Host Site



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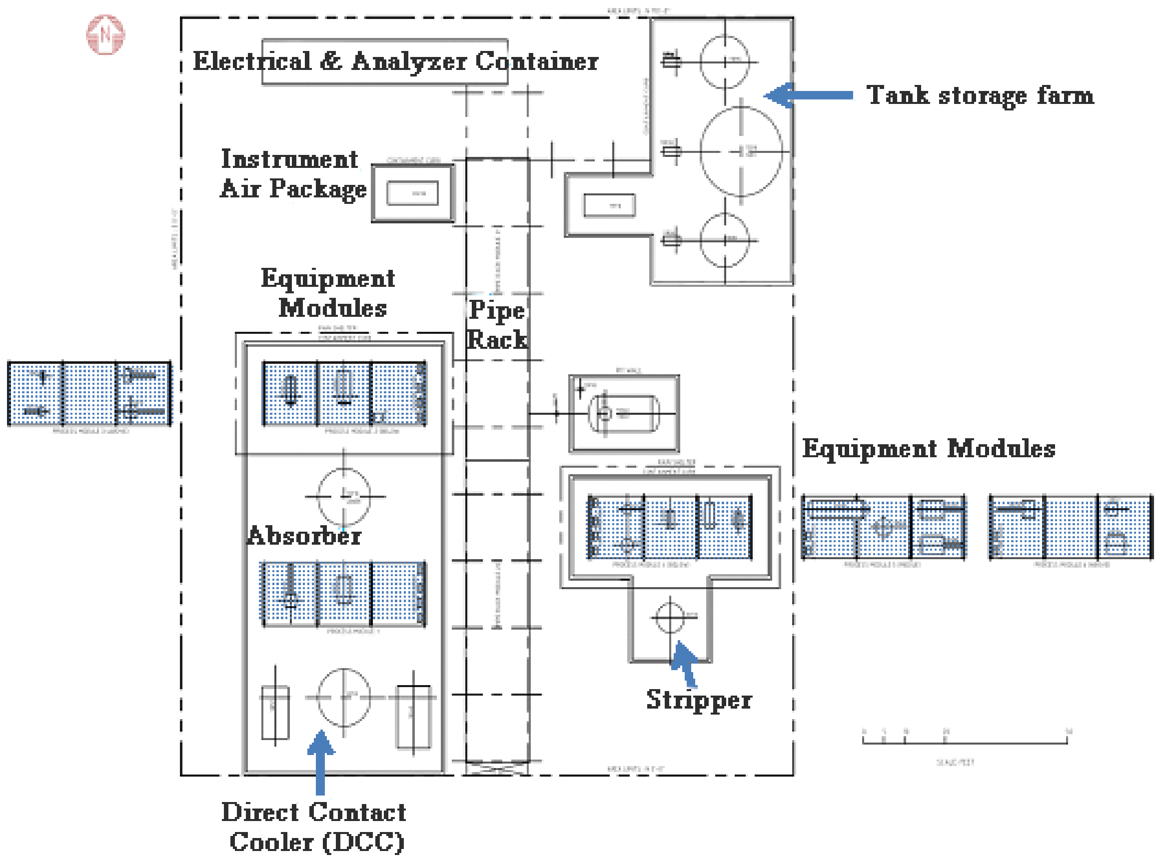
Plot Plan for Capture Plant

49 m x 46 m (160 ft. x 150 ft.) footprint

No modifications to existing plant combustion system (i.e. boilers) considered a major risk reduction by Abbott Power Plant



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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	1 Very Low	2 Low	3 Medium	4 High	5 Very High
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	**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.

TECHNO-ECONOMIC ANALYSIS

Process Performance and Cost Summary 550 MWe

Based on 1.5 MWe pilot test and Aspen Plus simulation results

Parameter	NETL Case 11	NETL Case 12	Linde Case LB1	Linde Case SIH
Scenario	No Capture	CO_2 Capture with MEA	CO_2 Capture with OASE® blue	CO_2 Capture with OASE® blue and SIH
Net power output (MWe)	550	550	550	550
Gross power output (MWe)	580.3	662.8	638.9	637.6
Coal flow rate (tonne/hr)	186	257	236	232
Net HHV plant efficiency (%)	39.3%	28.4%	30.9%	31.4%
Total overnight cost ($2011)	1,348	2,415	1,994	1,959
Cost of captured CO_2 with TS&M ($/MT)	N/A	67	52	50
Cost of captured CO_2 without TS&M ($/MT)	N/A	57	42	40
COE (mills/kWh) with TS&M cost included	81.0	147.3	128.5	126.5

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

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Energy Demand for 90% Capture and Compression

Linde process options reduce energy demand of CO_2 capture

Utility	NETL-MEA	Linde-BASF LB1	Linde-BASF SIH
Reboiler Duty, GJ/MT_CO_2)	3.61	2.61	2.30*
Cooling Duty (MS_{th}hr)/(MT_CO_2)	1.64	1.12	0.94
Electrical Power (kW_ehr/MT_CO_2)	119.9	102.95	104.16**

*Effect of stripper inter-stage heater (SIH): semi CO_2 lean solvent is reheated by hot CO_2 lean solvent exiting stripper

**Effect of additional solvent pump for SIH configuration adds 636 kW of electrical power

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Annual Operating and Maintenance Expenses

Novel solvent reduces annual operating expenses

Annual O&M Expenses for 550 MWe PC Power Plant with PCC (2011$)				
Case	NETL_2011 Case 12	Linde-BASF LB1-2011	Linde-BASF SIH-2011	Linde-BASF LB1-AFSC-2011
Total Fixed Operating Cost	64,137,607	57,356,056	56,777,693	56,557,758
Maintenance Material Cost	19,058,869	18,017,114	17,823,784	17,700,023
Water	3,803,686	3,595,777	3,557,193	3,532,493
Chemicals*	24,913,611	23,551,836	23,299,117	23,137,338
SCR Catalyst	1,183,917	1,119,204	1,107,195	1,099,507
Ash Disposal	5,129,148	4,848,789	4,796,760	4,763,454
By-Products	0	0	0	0
Total Variable Operating Cost	54,089,231	51,132,721	50,584,050	50,232,815
Total Fuel Cost (Coal @ 68.60$/ton)	144,504,012	136,605,442	135,139,620	134,201,266

*Includes cost of OASE blue® solvent for Linde-BASF PCC options

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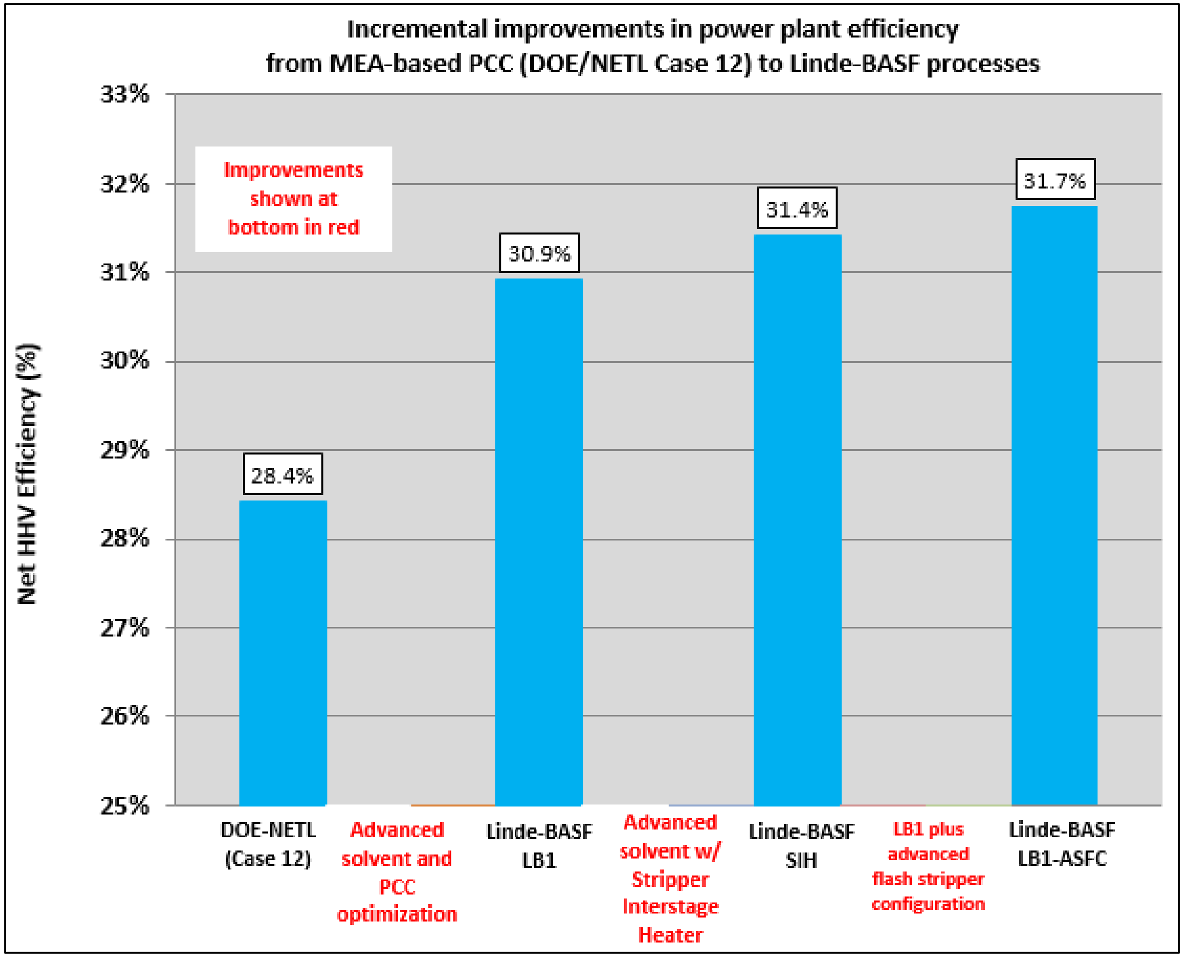
Process Performance and Cost Summary 550 MWe

Net higher heating value (HHV) efficiency (%) improvements



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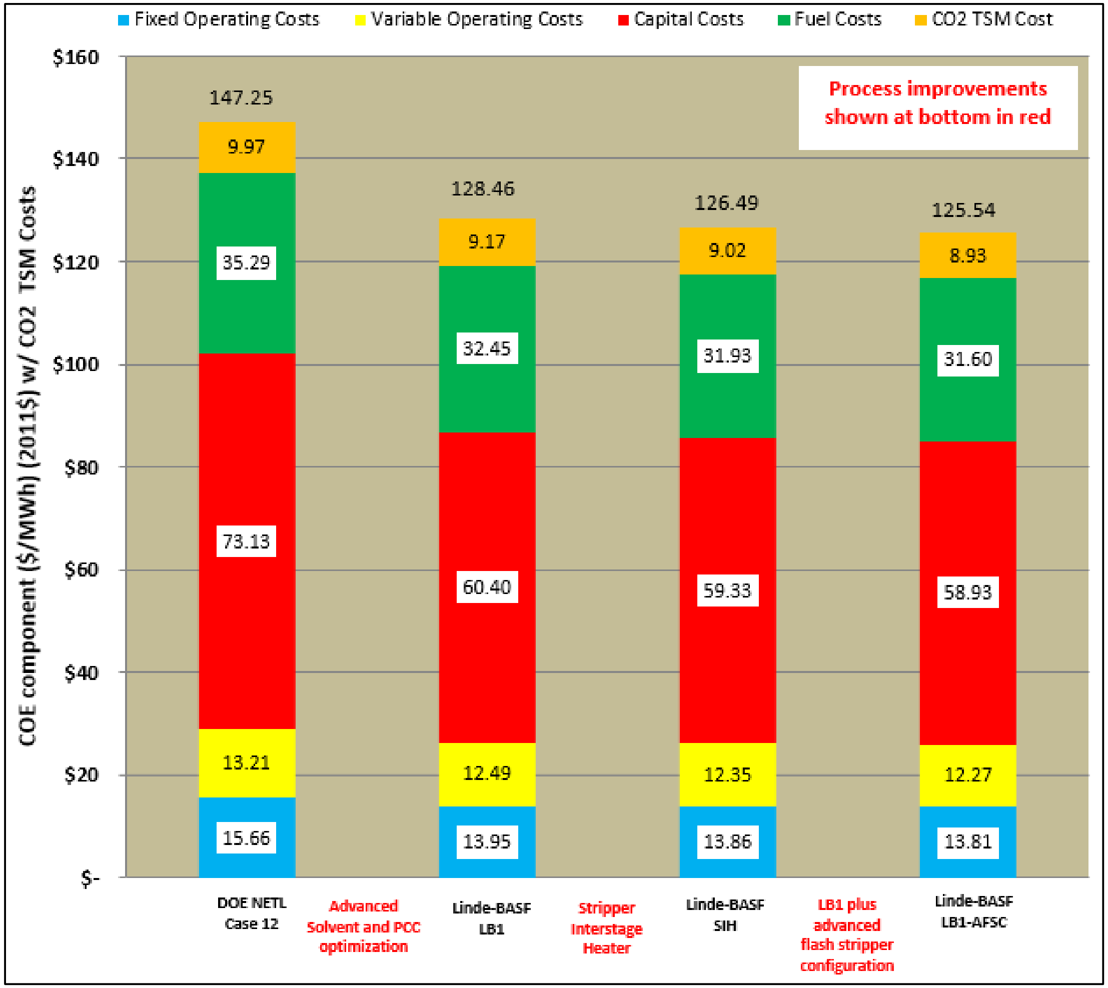
Process Performance and Cost Summary 550 MWe

Cost of electricity (COE) reduction ($/MWh) (2011$) with lower overall CAPEX and OPEX



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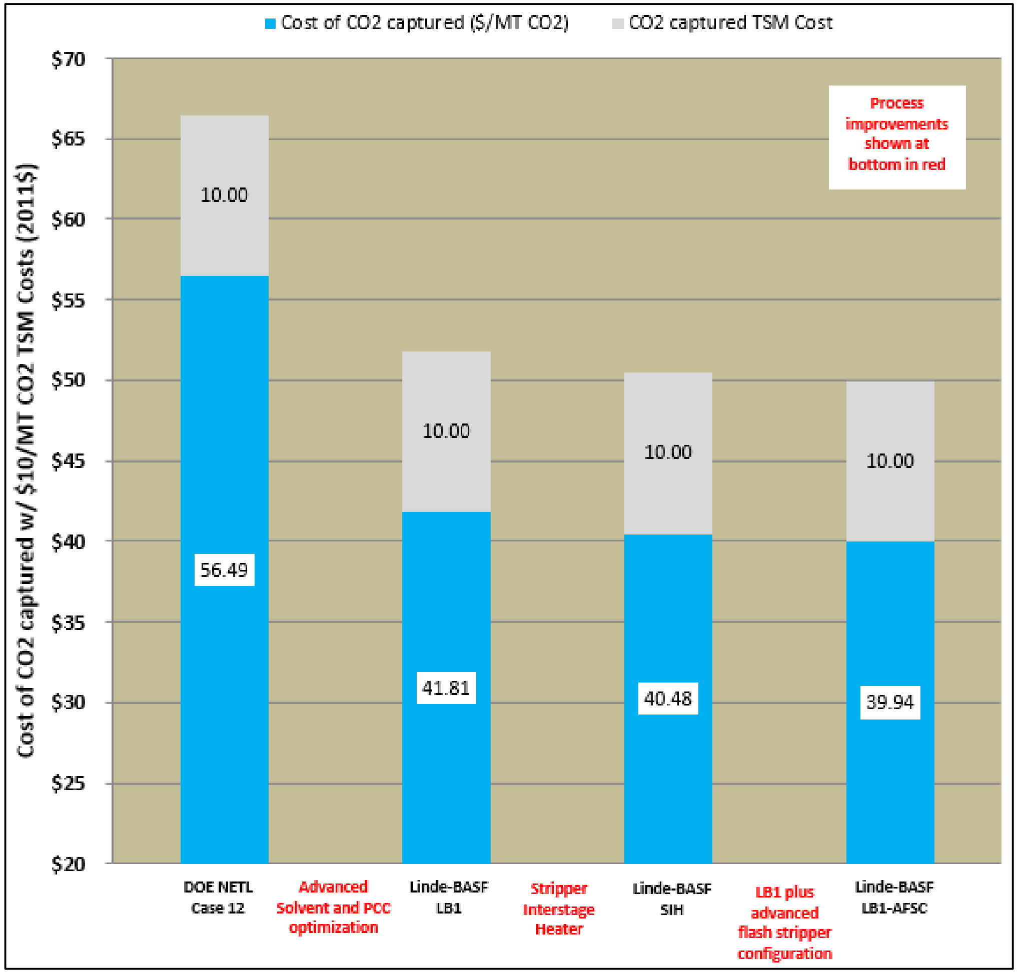
Process Performance and Cost Summary 550 MWe

Lower cost of CO_2 captured (\$/tonne CO_2) (2011\$) toward DOE target of \$40/tonne CO_2



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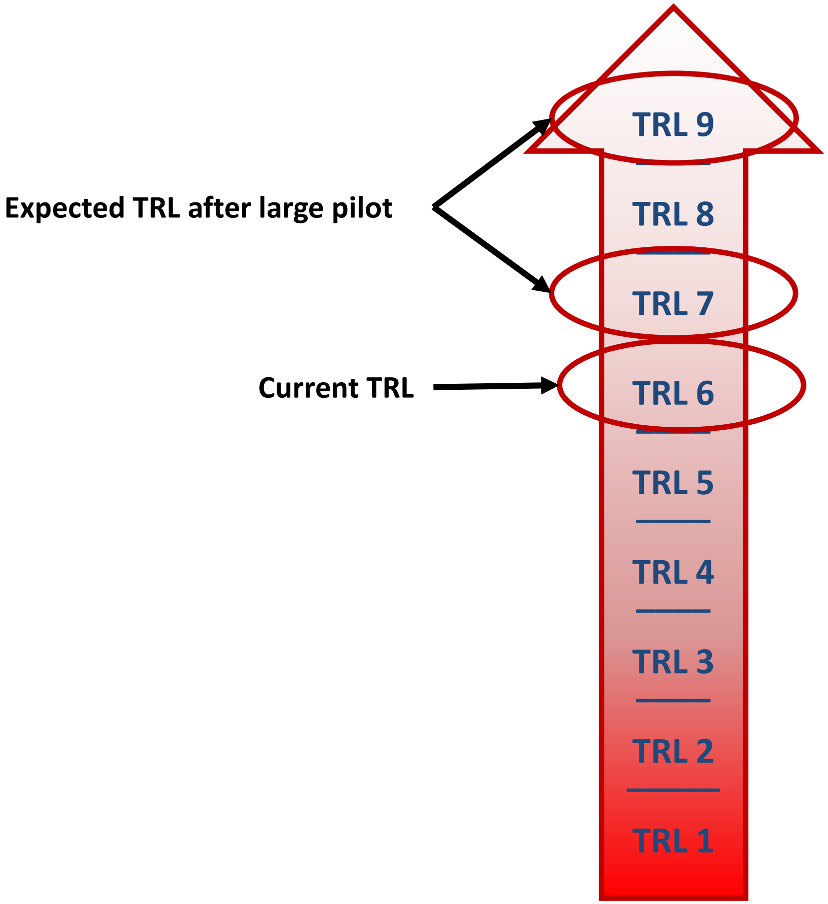
TECHNOLOGY GAPS

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

LESSONS LEARNED, AND PATH FORWARD

Lessons Learned

Technical & Permitting Regulatory

Technical

- Significance of solvent regeneration at high pressure (up to 3.5 Bar) on capital and operating cost reductions
- Significance of flexible reboiler design to allow proper PCC process dynamics during rapid power plant load fluctuations.
- Optimization of PCC process configuration to maximize waste heat utilization and ultimately minimize solvent regeneration energy consumption – results in inclusion of Stripper Inter-stage Heater (SIH) Significance of aerosol formation on solvent losses and related emission issues
- Center for utilizing captured carbon have spurred interest from other technology developers in CO_2 utilization

Permitting & Regulatory

- Importance of water demand on the permitting costs

Lessons Learned

Stakeholder Engagement & Workforce Development

Stakeholder Engagement

- Increased interest in retrofitting plants for carbon capture
- Potential impact of CCUS on the regional economy
- How the proper host site can become a training ground for the operation and maintenance of capture facilities

Workforce Development

- Working through groups like Association of Illinois Electric Cooperatives (AIEC) creates strong advocates for CCUS
- Potential to include education opportunities at the undergraduate and graduate level that enable students to understand the value of CCUS
- Opportunity to train future operators of capture facilities

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