Phase II / III Review: Large Pilot Testing of Linde-BASF Advanced Post-Combustion CO_2 Capture Technology at a Coal-Fired Power Plant (FE-0031581)

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PROJECT OVERVIEW

Complete

Phase II Funding: $3,736,684
DOE: $2,988,359
20% Cost Share: $748,325
Work Period: Sept. 1, 2019 – Jan. 15, 2021
Phase II Completed: May 31, 2021

Phase III Funding: $67,000,000
DOE: $47,000,000
Cost Share: $20,000,000 (supplied by the State of Illinois)
Phase III Complete: May 2026

City Water, Light and Power (CWLP) Springfield, IL

PROJECT OBJECTIVES:

Overall: Design, construct, and operate a 10 MW capture system based on the Linde / BASF advanced amine-based, post-combustion carbon dioxide (CO_2) capture technology at CWLP Dallman Unit 4, Springfield, IL.

Phase III: Build / Operate 10 MW capture system and compare performance with results from 1.5 MW testing at the NCCC. If successful, keep system for evaluating future capture and utilization testing technologies.

Part of Plan for Decarbonization of the Grid

WHY THE INVESTMENT BY THE STATE OF ILLINOIS?

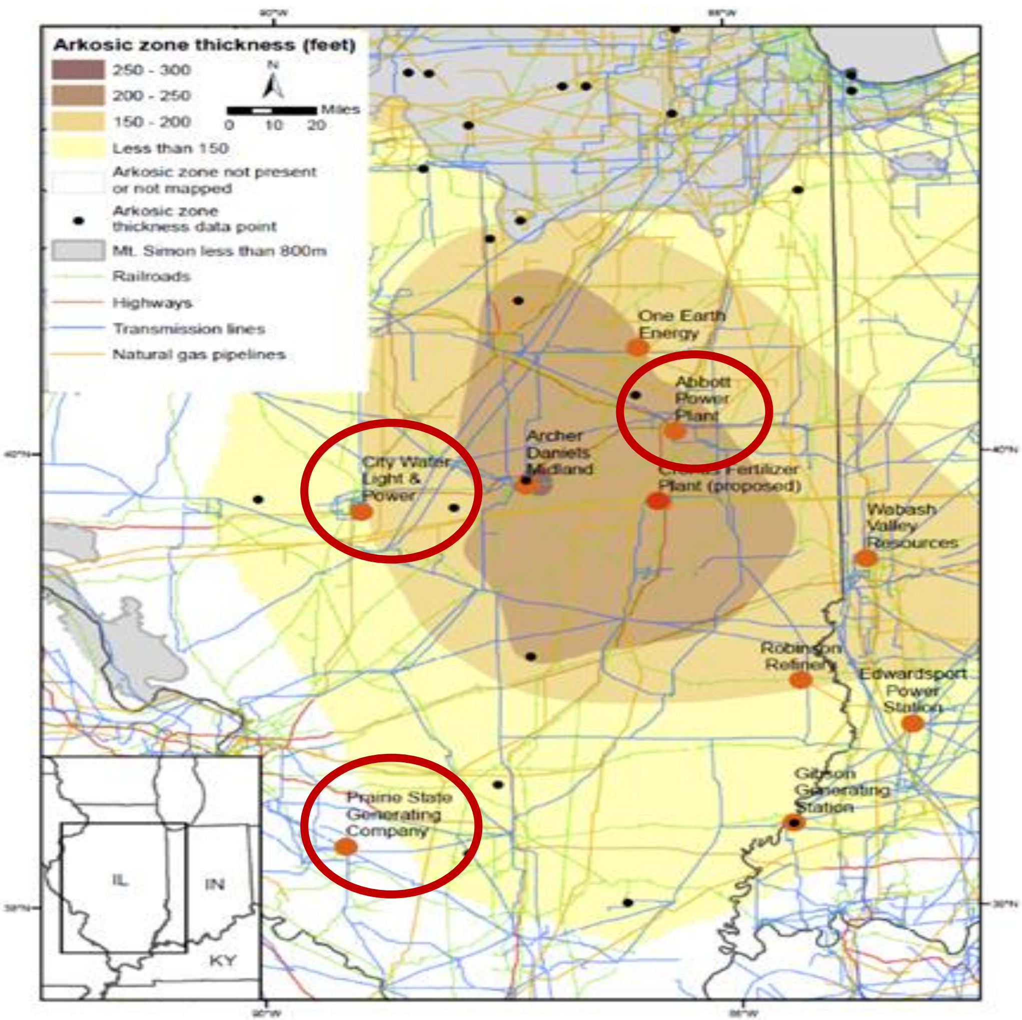
Illinois: A Confluence of Geology, Technology, Government Investment

Creates unique advantages for the state of Illinois

- Ability to store CO_2 has provided a major motivator for large capture pilots and large-scale capture demonstration projects at CO_2 emitters within the state
- Unique geology of Illinois a major asset for CO_2 storage
- 45Q has been a major incentive – a means to monetize CO_2
- US DOE funding has enabled the maturation of capture technologies that can be deployed at locations throughout the state
- State of Illinois' support with major cost share investment
- Elected officials at all levels interested in the job creation and regional economic benefits of these projects

Capture Studies Coordinated with Geological Storage Studies

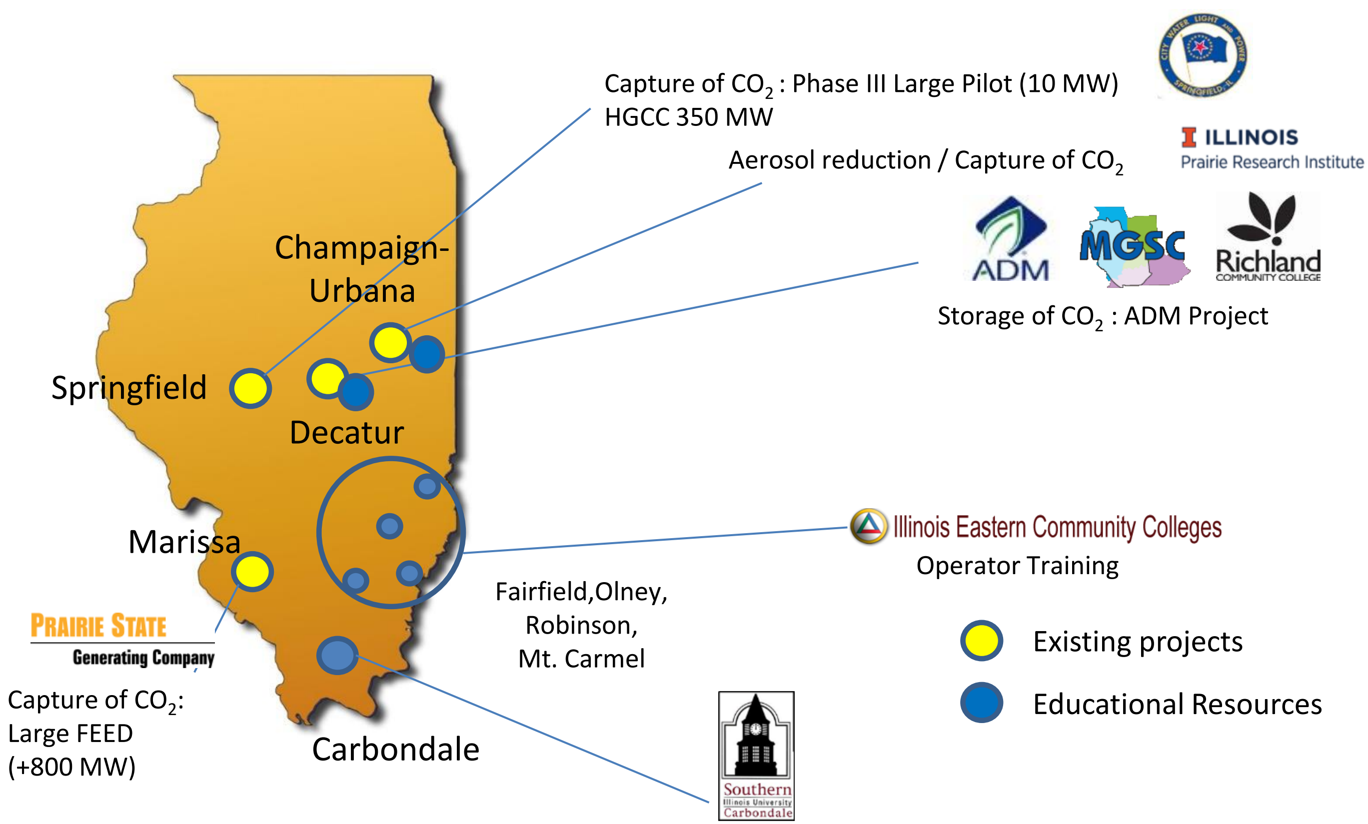
CarbonSAFE Phase III: Geological Storage



- ***Able to connect to CarbonSAFE's Phase III Illinois Geological Storage Corridor***
- ***Sufficient CO_2 geological storage capacity near the host sites***
- ***All sites within 100 miles of storage site***
- ***Immediate access to Interstate highway***

Illinois: Knowledge Base for Carbon Capture & Storage

Concentration of natural resources and intellectual capital

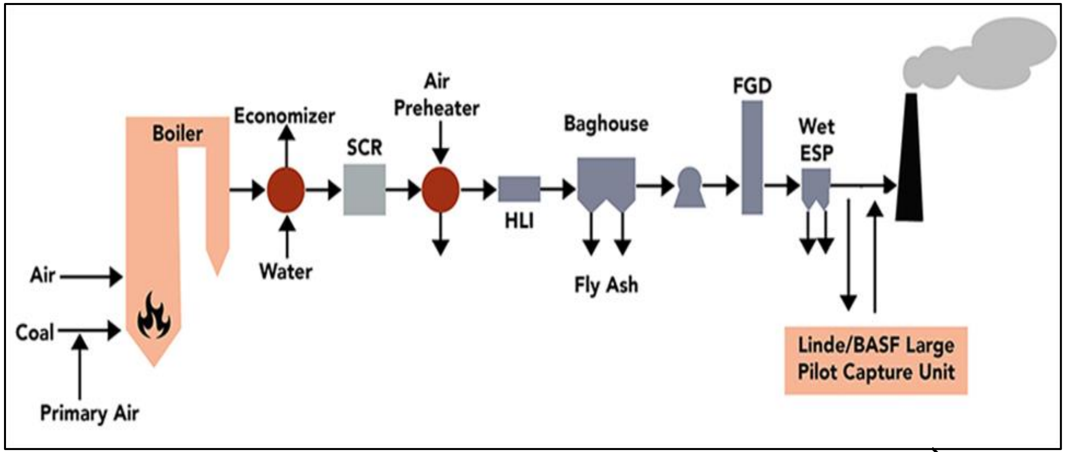


Build / Operate: Largest Capture R&D Pilot in the World (10 MW)

CITY, WATER, LIGHT AND POWER

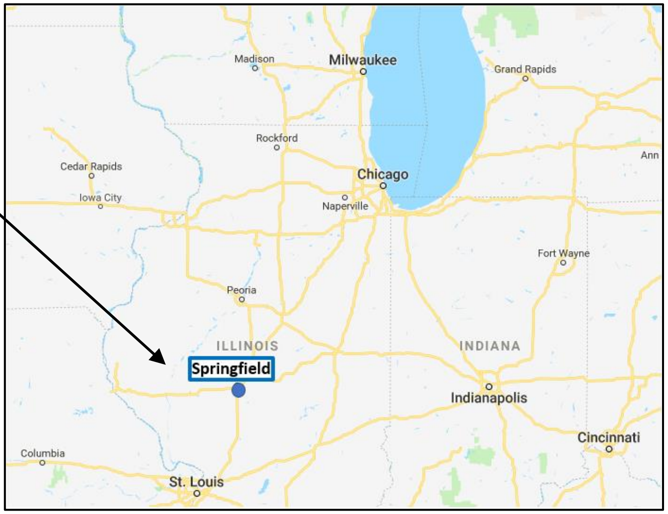
CWLP Location and Configuration

Traditional PC plant



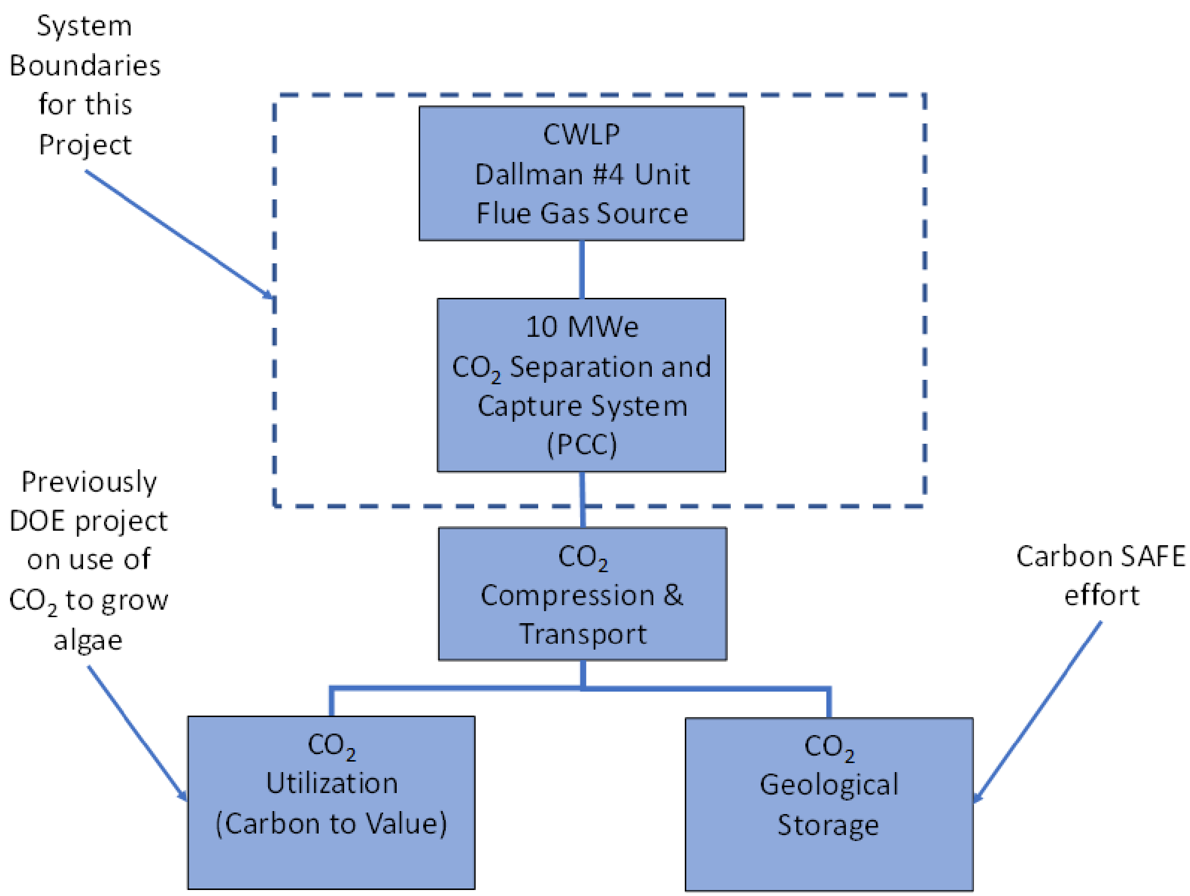
Dallman Unit 4 configuration

Location of city of Springfield within the state of Illinois



System Boundaries for Project

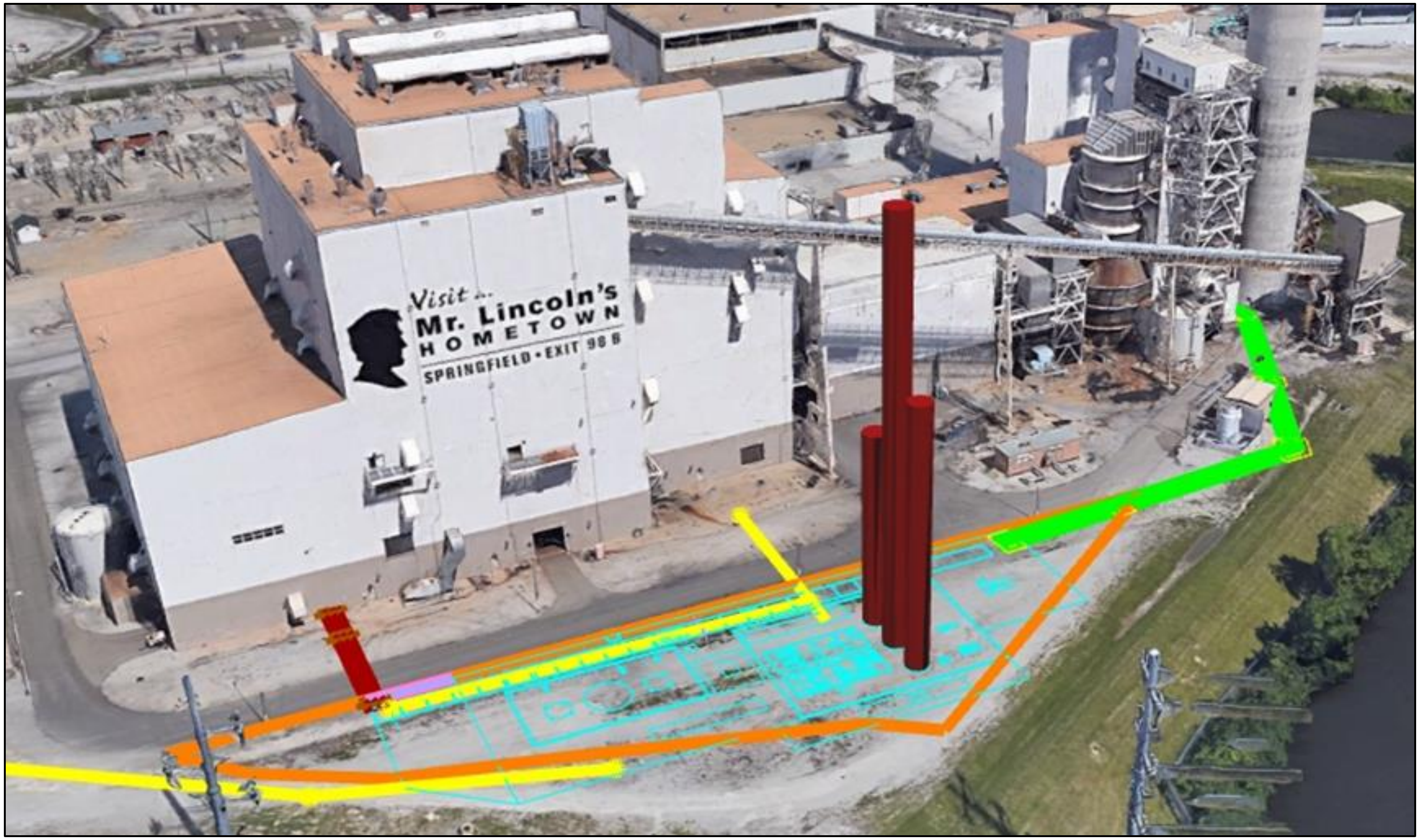
Follow-on projects can connect to existing DOE projects for storage and utilization



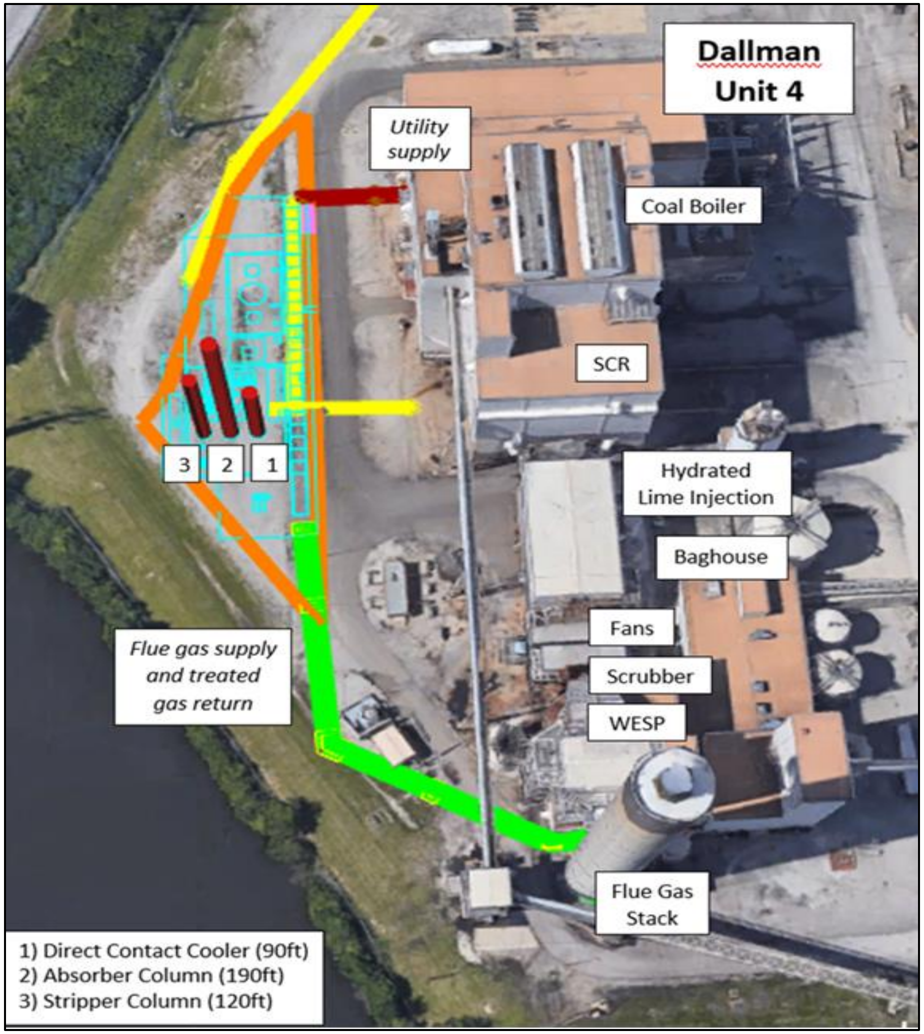
ILLINOIS Prairie Research Institute
BASF We create chemistry
AEI Affiliated Engineers
ACS Design · Construction · Integration
NATIONAL ENERGY TECHNOLOGY LABORATORY
U.S. DEPARTMENT OF ENERGY

City Water, Light and Power (CWLP)

Water and power supplier for City of Springfield



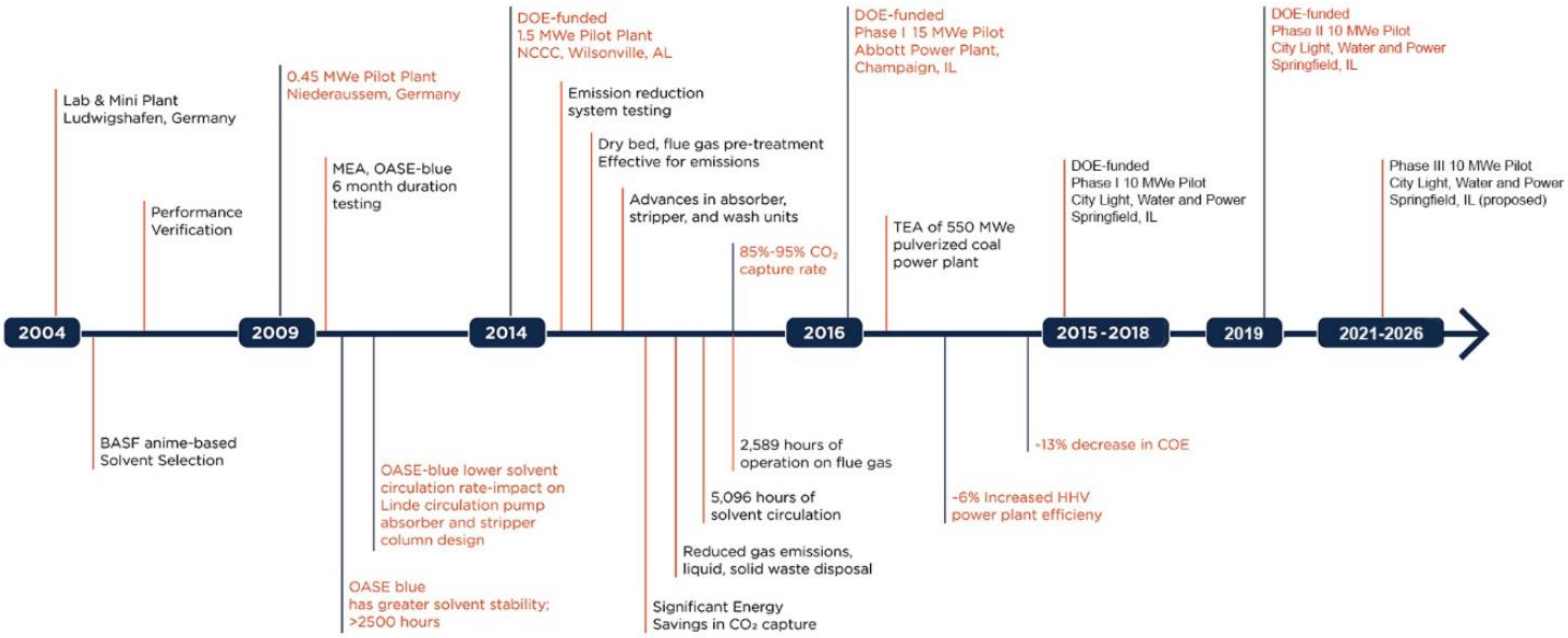
Capture Plant and Tie-Ins to Plant – Birds-Eye View



TRL of Capture System Ready for 10 MW Scale

TECHNICAL BACKGROUND

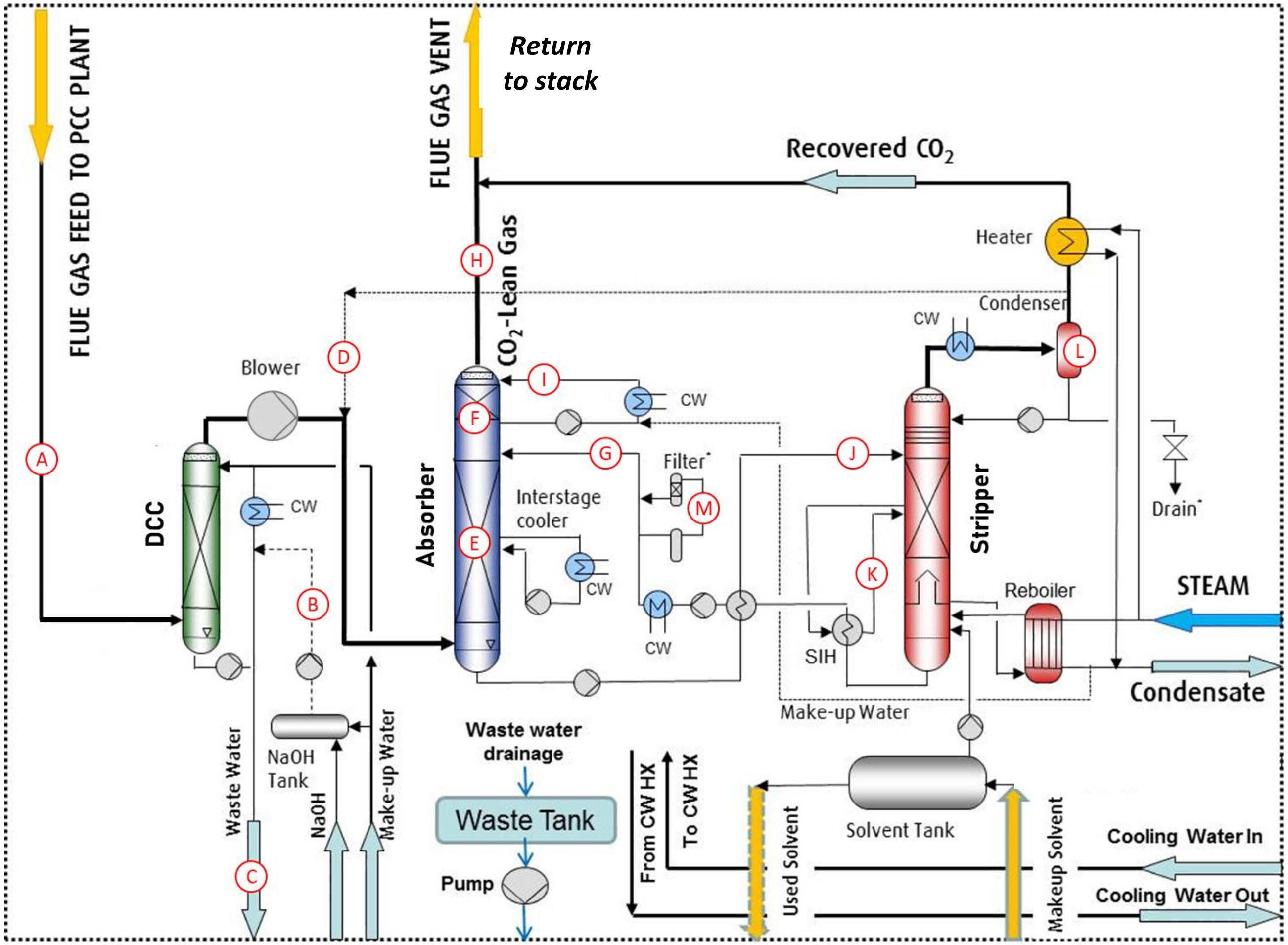
Linde / BASF Milestones



Linde / BASF Solvent Based Capture System

Reduced capital costs / energy costs
- Optimized BASF OASE® blue solvent
- Efficient CO_2 capture from low-pressure sources
- Longer solvent stability
- Lower solvent circulation rate

Notable Linde process improvements
(F, E) Dry bed water wash design to minimize solvent losses
(J) Stripper regeneration at 3.4 bars reducing CO_2 compressor cost and power consumption
(K) Advanced Stripper Interstage Heater to reduce regenerator steam consumption.



Scale-up Factors at Each Stage for Development

DEVELOPMENT SCALE	YEAR	SIZE (MWe)	SCALE-UP FACTOR*	DEVELOPMENT STRAGETY
Lab scale; mini pilot	2004	0.015	n/a	Solvent selection and proof-of-concept under laboratory conditions
Bench scale: Niederaussem	2009	0.45	30	Solvent performance validation; emissions control testing under realistic conditions
Small pilot: NCCC	2016	1 to 1.5	3	Validation of unique process features aimed at reducing CAPEX – i.e. high capacity structured packing, gravity-driven absorber inter-stage cooler, and unique reboiler design
Proposed large-scale pilot	2021-2026	10 to 12	7 to 8	Equipment performance validation at commercially relevant scale (i.e. uniform gas/liquid distribution in absorber and inter-stage heating in the stripper)
First commercial plant	2025-2030	200 to 600	20 to 50	At scale demonstration of complete CCS value chain (capture, compression, transport, and storage/ utilization)
nth commercial plant	2030+	600+	3 to 5	Safe, reliable, and economic operation in compliance with regulations

**Assumes PCC capacity of 20 tpd captured CO_2 for every 1 MWe (flue gas 13% CO_2 concentration)*

TRL Improvement of Key Subsystems

Subsystem	Current TRL	Comments	Expected TRL
Absorber and Stripper Columns	6	At larger column diameters, the importance of uniform liquid and gas distribution and proper design of feed inlets and gas liquid offtakes become critical to achieve predicted pe1fonnance of the target CO_2 capture rate and minimum regeneration energy. In addition, a proper build and install strategy is required in order to achieve the lowest cost option at scale.	7(9)*
Heat Exchangers and Reboiler	6	Plate-fin exchangers have been used in the pilot plants and will be scaled up for the large pilot. The large pilot reboiler design will be selected as appropriate for the advanced stripper design configuration.	7
Stripper Heat Integration and Recovery	6	Prior to the lean-rich heat exchange, the large pilot will incorporate a stripper inter-stage heater to use heat recovered from the CO_2-lean solvent to vaporize semi CO_2-lean solvent from an intermediate section of the stripper column. Detailed design has shown the energy reduction possible and this will be validated in the large pilot.	7
Materials of Construction	6	Several materials including carbon steel, different stainless-steel options, fiberglass reinforced plastic (FRP) and concrete sections with polypropylene in-liners have been tested and evaluated in the pilot plants. The materials for the large pilot will be specified based on the results from the current pilot plant analysis.	7
Emission Control	6	Solvent emissions minimization well below air emissions compliance limits is a key success factor for commercial implementation of a solvent-based post-combustion capture system. Assessment of key operating parameters and flue gas aerosol reduction options will be validated at the proposed pilot.	7
Solvent Management	6	Scale-up involves management of a much larger inventory of solvent, introducing complexity in the logistics of delivery and storage. Experience from other amine-based commercial systems, such as intermediate solvent storage and delivery, and solvent reclamation and recycling, will be considered for the large pilot.	7

* TRL 9 based on Linde's related experience in building up to ~12m diameter columns for other commercial applications. This has been validated in other commercial-scale aiming operations and will be applied in the large pilot.

Attractive Techno-Economics for Linde / BASF Process

Baseline case: DOE-NETL supercritical PC power plants

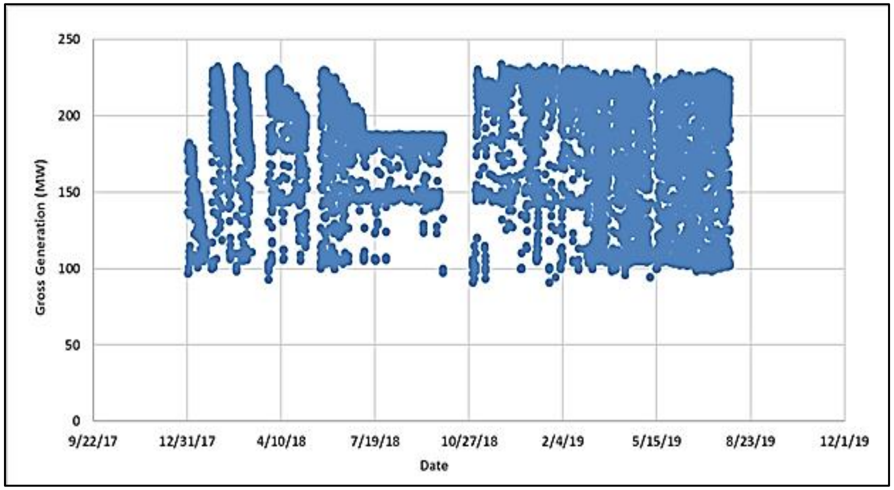
Parameter	DOE NETL Case B12A	DOE NETL Case B12B	Linde BASF LB1	Linde BASF SIH	Linde BASF VHR
Description	**No CO_2 Capture**	**90% Capture w/ Cansolv PCC process**	**90% Capture w/OASE® Blue**	**90% Capture w/ OASE® Blue and SIH**	**90% Capture w/ OASE Blue® SIH, and WHR**
Net Power Output (MWe)	550	550	550	550	550
Gross Power Output (MWe)	580	642	630.4	629.3	626.3
Coal Flow Rate (tonne/hr)	179.2	224.8	221.9	218.5	210
Net HHV plant efficiency (%)	40.70%	32.50%	32.97%	33.40%	34.73%
Total Overnight Cost ($2011) ($/MT)	$1,379	$2,384	$1,970	$1,950	$1,921
Cost of CO_2 captured with T&S ($/MT)*	N/A	$68.00	$53.58	$52.71	$51.31
Cost of CO_2 captured without T&S ($/MT)*	N/A	$58.00	$43.58	$42.71	$41.31
COE ($/MWh) with T&S*	$82.30	$142.80	$127.97	$126.50	$123.63
PCC specific reboiler duty (MJ/kg CO_2)	N/A	2.48	2.60	2.30	1.50

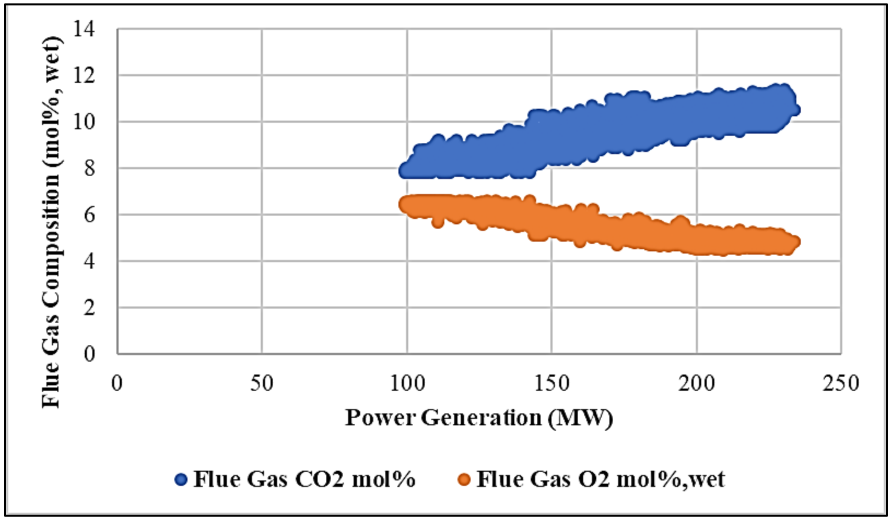
Case implemented in Phase III

Future Trends: Designing for Variation in Plant Loads

Capture system design accommodates this variation in gross generation

Just like the DOE vision for future power plants, over the 18-month period the plant demonstrated a consistent variation in gross generation between the limits of 100 MW and 225 MW





- **Increase in CO_2 concentration in the flue gas with increasing load on the power plant**
- **Inverse relationship between O_2 concentration and increasing load**
- **May conceivably happen when the plant operates at lower capacities, without adjusting the air intake to the turbine**
- **Flue gas is effectively diluted as the ratio of combustion air to combustion fuel in higher at lower power generation**

Phase III: Evaluating Linde/BASF Technology vs. DOE Power Plant Vision

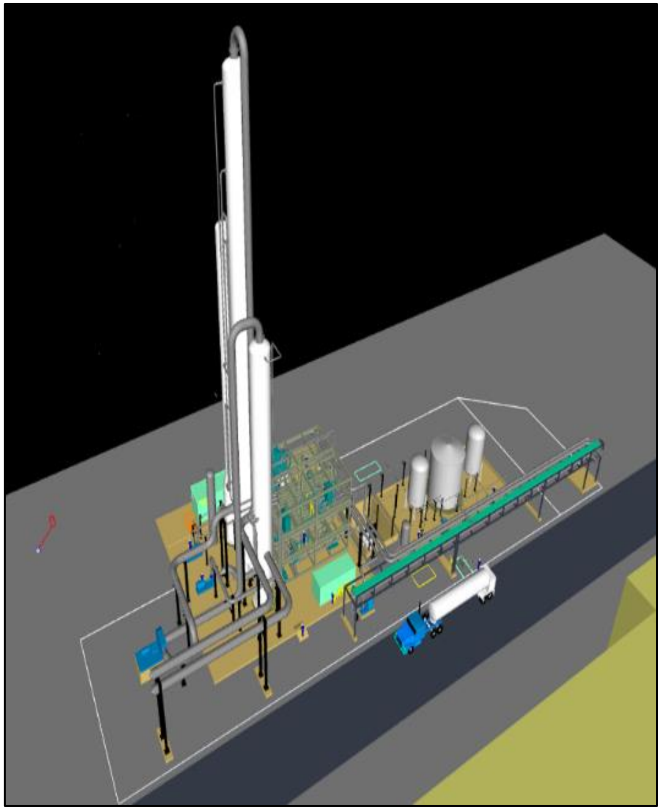
Grouping	Qualities in Grouping	Previous Evaluations	Evaluations During Phase III
Flexibility & Efficiency	(10) Integrated carbon capture, +90% capture (1) High overall plant efficiency (3) Capable of high ramp rates and minimum loads	• 1 MWe at NCCC (1.B.4)	• Measurements made during long-term testing • Updating of TEA • Host site load varies, capture system ability to follow will be demonstrated (1.A.5)
CAPEX and OPEX	(6) Reduced design, construction, and commissioning schedules (7) Enhanced maintenance features	• Outlined in previous TEA developed for 1 MWe	• Tracked during build / operate of Phase III • Updated TEA will address
Environmental Footprint	(2) Near-zero emissions (5) Minimized water consumption	• 1 MWe at NCCC (1.B.4) • NEPA addressed these issues	• Permits require measurements during testing
Changes to Upstream Processes of Power Plant	(4) Integration with energy storage (8) Integration with coal upgrading (9) Capable of natural gas co-firing	• Capture technology integrated with energy storage in 21st Century Power Plant (DE-FE0031995) and H_2 energy storage DE-AR0001310 • Testing at small sizes were conducted with various types of coal • Included in natural gas fired systems studies	n/a

HAZOP Review – Recommendations & Responses

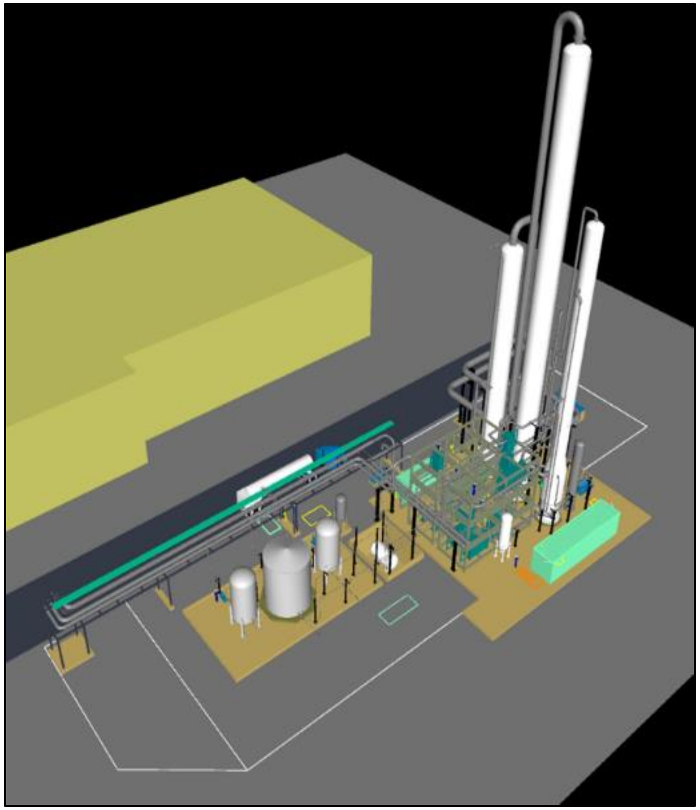
Recommendation	Mitigation and Response Strategy
Check safety measures upstream	Host site confirmed there is no foreseen likelihood of a negative pressure situation, the controls will be designed to shut down the pilot plant and dampers in the event of an upset
Check maximum possible pressure from boundary limit	Confirmed maximum pressure that could occur at the battery limit from the wet ESP if ID fans are on with no recycle pumps
Heat tracing required for low points in OSBL flue gas lines	Project will make every attempt to design OSBL flue gas lines at a constant slope with no low points – if low points must exist, they will include heat traced drain lines
Check maximum possible temperature at boundary limit	Confirmed maximum design temperature that could occur at the battery limit from the wet ESP and declared PPE requirements
Check maximum allowable amine emissions per local regulations	Confirmed maximum permissible amine emissions (categorized as VOC/VOM) based on Dallman 4 air permit limit and emission test results

Linde/BASF Capture Unit

3D rendering



Looking down from power plant



Looking back towards power plant

Transitioning from Phase II to Phase III

PROJECT MANAGEMENT & RISK MANAGEMENT

Prairie Research Institute: Addressing Societal Issues

Structure creates ability to address the many factors for large projects

ILLINOIS

ILLINOIS
Prairie Research Institute

Potential Endangered Species

Water

Storage

ILLINOIS
Illinois Natural History Survey
PRAIRIE RESEARCH INSTITUTE

ILLINOIS
Illinois State Water Survey
PRAIRIE RESEARCH INSTITUTE

ILLINOIS
Illinois State Geological Survey
PRAIRIE RESEARCH INSTITUTE

ILLINOIS
Illinois State Archaeological Survey
PRAIRIE RESEARCH INSTITUTE

ILLINOIS
Illinois Sustainable Technology Center
PRAIRIE RESEARCH INSTITUTE

Potential Artifacts

Capture

Phase III: Project Management Structure

Consistent team throughout all phases

HOST SITE
City, Water, Light & Power, Springfield, IL
P.J. Becker

ILLINOIS
Awardee
University of Illinois (UIUC)
Dr. Kevin C. O'Brien, PI
Stephanie Brownstein, Project Manager
Project management, permitting, operations, interface with CWLP

Commercialization

SUBAWARDEE
Linde Engineering, Americas (LEA)
Jason Haley, Co-PI
Matthew Parker, Project Manager
Detailed engineering **ISBL** Components
Procurement and Construction Management, **ISBL** Components

SUBAWARDEE
Affiliated Construction Services (ACS)
Greg Larson
Procurement and Construction Management, **OSBL** components

OSBL
ISBL
OASE® blue solvent

Linde Engineering Dresden (Linde GmbH)
Torsten Stoffregen
Detailed engineering **(ISBL)**, start-up and testing support

Linde Inc.
Dr. Krish Krishnamurthy, Co-PI
Makini Byron, Project Manager
Testing & data analysis, project reporting

BASF
John Nichols
Manufacturing, supply of solvent and on-site training, solvent stability analysis

Affiliated Engineers Inc. (AEI)
David Guth, LEED AP
Engineering Design of **OSBL** components

Project Tasks

BP1 for Phase III = BP3 overall for project

Task #	Task	BP
1.0	Project Management and Planning	All BP
2.0	Baseline Techno-Economic Analysis (TEA)	BP3
3.0	Detailed Engineering and Specifications	
4.0	Permit Application	
5.0	Construction and Execution Plan	
6.0	Equipment Procurement	BP4
7.0	Site Preparation and Foundations Installation	
8.0	Plant Construction and Installation	
9.0	Commissioning and Test Plan	
10.0	Start-up and Operations	BP5
11.0	Operations and Testing	
12.0	Analysis of Test Campaign Results	
13.0	Updated Techno-Economic Analysis (TEA)	
14.0	Update of EH&S Assessment, TMP, and TCP	
15.0	Dismantling and Removal	

Task vs. Responsible Organization

WBS #	WBS Title	UIUC	Linde	ACS	BASF
1	Project Management and Planning	X	X	X	X
2	Baseline TEA		X		
3	Detailed Engineering and Specifications		X	X	X
4	Permit Application	X			
5	Construction and Execution Plan		X	X	
6	Equipment Procurement		X	X	
7	Site Preparation and Foundations Installation	X		X	
8	Plant Construction and Installation		X	X	
9	Commissioning and Test Plan	X	X		
10	Start-up and Operations	X	X		X
11	Operations and Testing	X	X		X
12	Analysis of Test Campaign Results	X	X		
13	Updated TEA		X		
14	Update of EH&S Assessment, TMP, and TCP	X	X		
15	Dismantling and Removal	X	X		

Milestones for Phase III

BP1 for Phase III = BP3 overall for project

Budget Period	Task Number	Description	Verification Method
3	1	Updated Project Management Plan	Project Management Plan file
3	1	Phase III Kickoff Meeting	Presentation file
3	4	Permitting Issuances Complete	Quarterly RPPR file
3	3	Detailed Engineering Complete	Quarterly RPPR file
4	6	Equipment Procurement and Fabrication Complete	Quarterly RPPR file
4	8	Construction & Installation Complete	Quarterly RPPR file
5	10	Commissioning and Pre-Start-up Checks Complete	Quarterly RPPR file
5	10	Steady-State Operations Established	Quarterly RPPR file
5	11	Parametric Testing Complete	Quarterly RPPR file
5	11	Steady-State Testing Complete	Quarterly RPPR file
5	13	Updated TEA	Report file
5	14	Updated EH&S / TMP / TCP	Report file
All	1	Quarterly RPPR report	RPPR files

Transition from Phase II to Phase III – Risk Mitigation

RISK AREAS/FACTORS	RESULTS FROM PHASE II THAT MITIGATE RISKS
Permitting / Regulatory	- All permitting agencies identified and extensive discussions held with agencies - Costs detailed for permits - Per instructions of agencies, documents for permit applications prepared and ready to submit - Applications informally reviewed - Submit applications in BP1 of Phase III
Cost share	- Cost share obtained from state and schedule developed for disbursing funds - Cost share disbursement schedule designed based on procurement and construction schedule
Interconnection of Utilities from host site to capture plant	- Detailed design of ISBL and OSBL slightly enhanced in Phase II to facilitate ease of interconnection - On-going communication between ISBL EPC (Linde) and OSBL EPC (ACS) enables understanding of responsibilities - Resolved means to design OSBL in order to avoid obstacles presented by existing infrastructure at host site - On-going communication with host sites assured volumes and quality of utilities are available for hook-up
Procurement	- Large equipment has bid ready documents developed during Phase II for both ISBL and OSBL - Identification of long-lead time procurements - Discussions with solvent supplier (BASF) on volume needs, timing, and logistics - Procurement schedule developed to assure project is not delayed
Labor costs for construction	- Union labor required for construction and operation of the plant - Engaged with labor unions to educate them on project and understand rates/concerns - Strong support from unions for construction and operation - Rates established and built into construction and operation costs - Qualifications required of contractors who can perform work at host site established - Potential local contractors (electrical, plumbing, welding, etc.) identified
Operational costs to run capture plant	- Working with host site, operational costs (i.e. extra coal, steam, etc.) established - Host site will be compensated for extra costs incurred during operation of the capture facility - Avoids the need to approach rate payers and seek reimbursement from them for costs of operation
Variation in flue gas composition with variation in plant load	- Characterized flue gas based on load on host site - CO_2 and O_2 levels varied with load - Established design to accommodate variations in plant load
Cost overruns during construction	- Pre-engineering of major equipment in Phase II to improve the quality of bids received from vendors

NEPA

A NEPA working team was formed consisting of the NEPA contractor, ISTC, Linde, CWLP, and NETL/DOE

- NETL and DOE approved the Final EA and FONSI
- Created an Inadvertent Discoveries Plan based on feedback from regional Nations

PERMITTING

A working team for permitting issues was formed consisting of representatives from ISTC, CWLP, and the Illinois Environmental Protection Agency (IEPA)

- **Stormwater** – a construction permit will be submitted by project contractor; stormwater from project area covered by site NDPES permit
- **Air emissions** – emission values have been calculated; construction/operating permit will be managed as a “Modification to the Facility”
- **Hazardous waste** – a permit is not required; solvent contaminated waste will be tested to determine hazardous status and dispose appropriately
- **Wastewater** – 3rd party wastewater assessment complete; initial treatment design and costing complete

Job Creation and Environmental Justice Concerns

Important additional study conducted as part of Phase III

- Job Creation study was completed with non-project funds for Phase II
- Examined direct, indirect and induced job creation
- Phase III operation will employee some of plant workers that would have been laid-off due to shut down of older units
- Follow-up job creation study important to compare predicted vs. actual
- Environmental Justice of major interest since Qualified Opportunity Zones (QOZs) present in city of Springfield

Summary and Conclusions

- Legislation at the Federal Level and State Level has stimulated interest in CO_2 capture for both power generation and industrial applications
- US DOE funding for both capture and storage has been critical to stimulate efforts
- Large projects create learnings that cannot be otherwise obtained
- Phase III is an important evaluation of Linde / BASF capture technology
- Phase III viewed as having a great potential to stimulate job formation (direct, indirect, and induced)
- Phase III Environment Justice impact of interest since Qualified Opportunity Zones nearby

Acknowledgements

Organization	Name
Andrew Jones	National Energy Technology Laboratory / US Department of Energy
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Krish Krishnamurthy, Makini Byron, Jason Haley, Lars-Erik Gaertner, Devin Bostick, Tom Rayhill, Matthew Parker	Linde
John Nichols	BASF
David Guth	Affiliated Engineers Inc (AEI)
Greg Larson	Affiliated Construction Services (ACS)

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