Phase I Results:

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

Presenter: Kevin C OBrien, PhD
Director, Illinois Sustainable Technology Center
Prairie Research Institute
University of Illinois, Urbana-Champaign

2016 NETL CO2 Capture Technology Project Review Meeting
August 08 - 12, 2016
Pittsburgh, PA

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Funding, Objectives, Tasks, Timelines

PROJECT OVERVIEW

Prairie Research Institute (PRI) at University of Illinois
Illinois-focused Resource Research and Service

Addressing societal challenges that impact Illinois and the global community

1867

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ILLINOIS NATURAL HISTORY SURVEY
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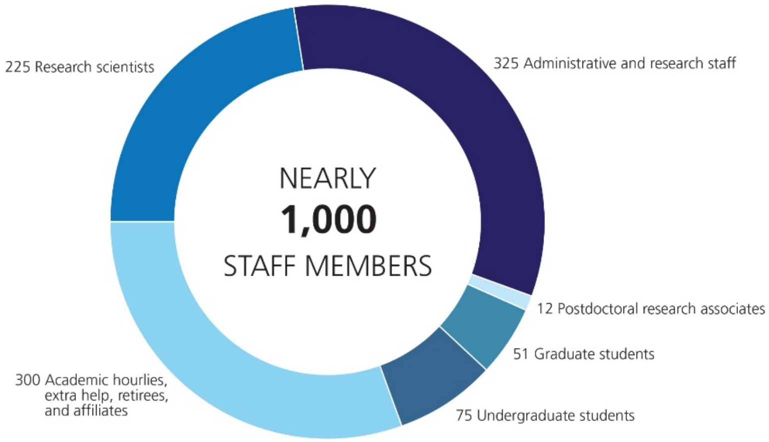
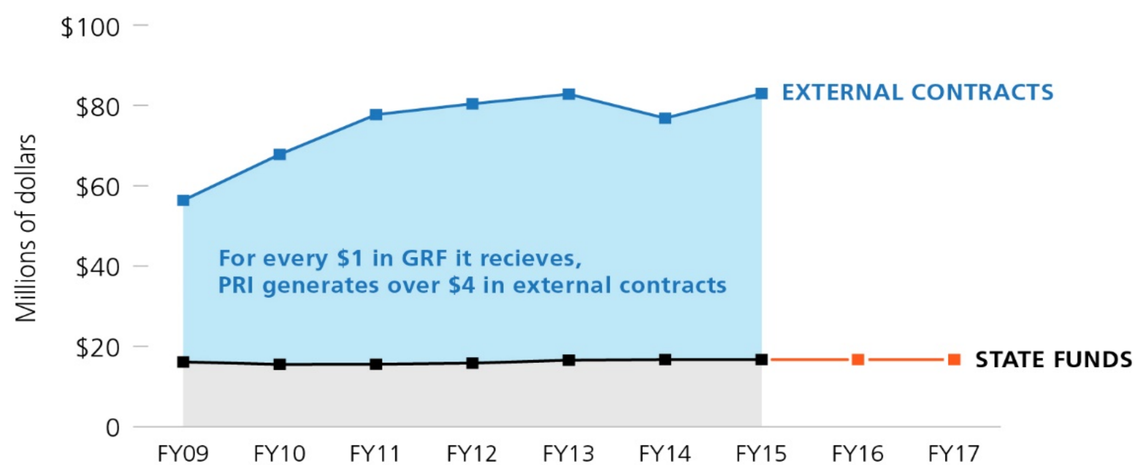
PRI : Skilled at Leveraging State Funds

History of executing large projects for the state and region





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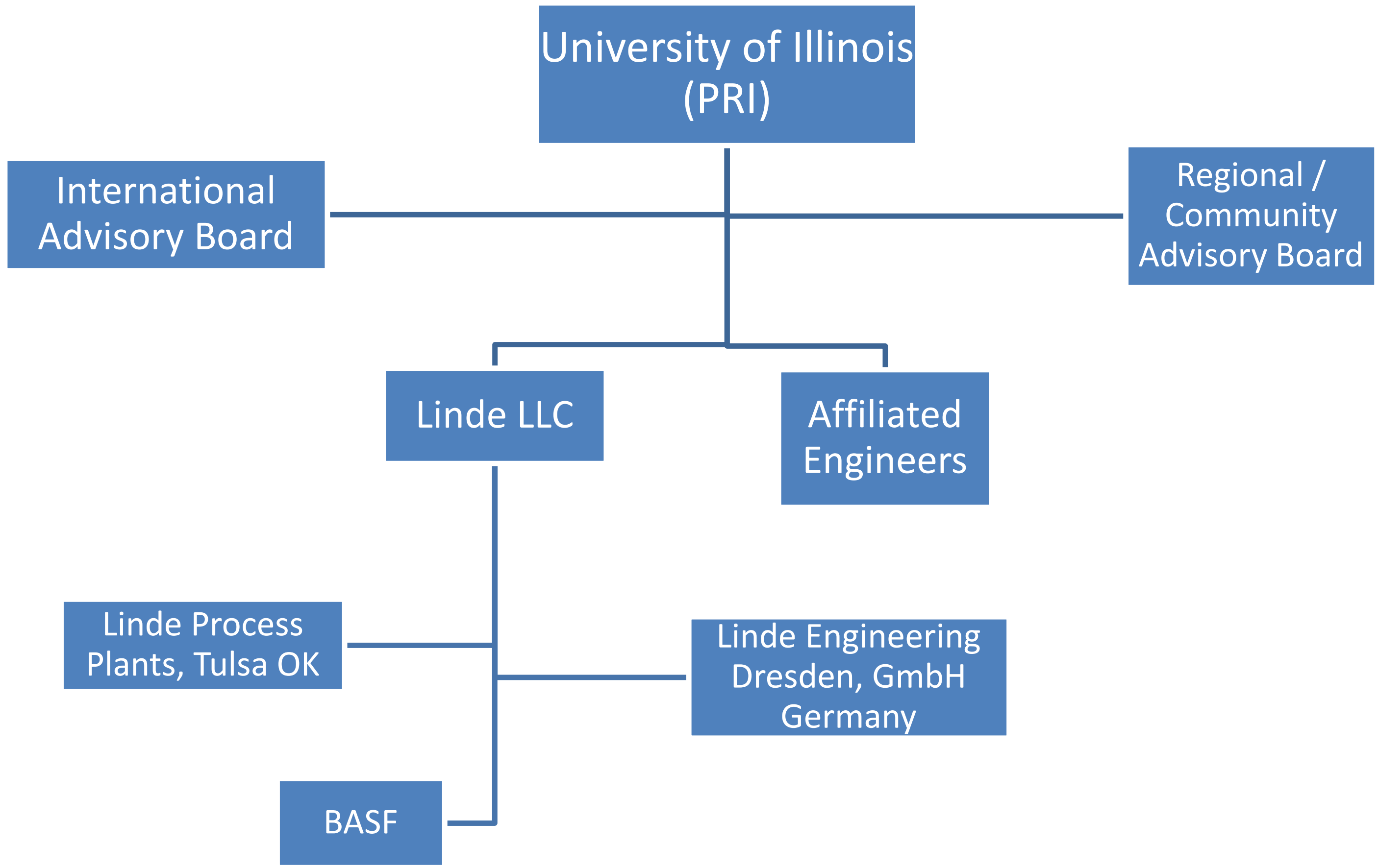
Phase 1: Project Organization Chart



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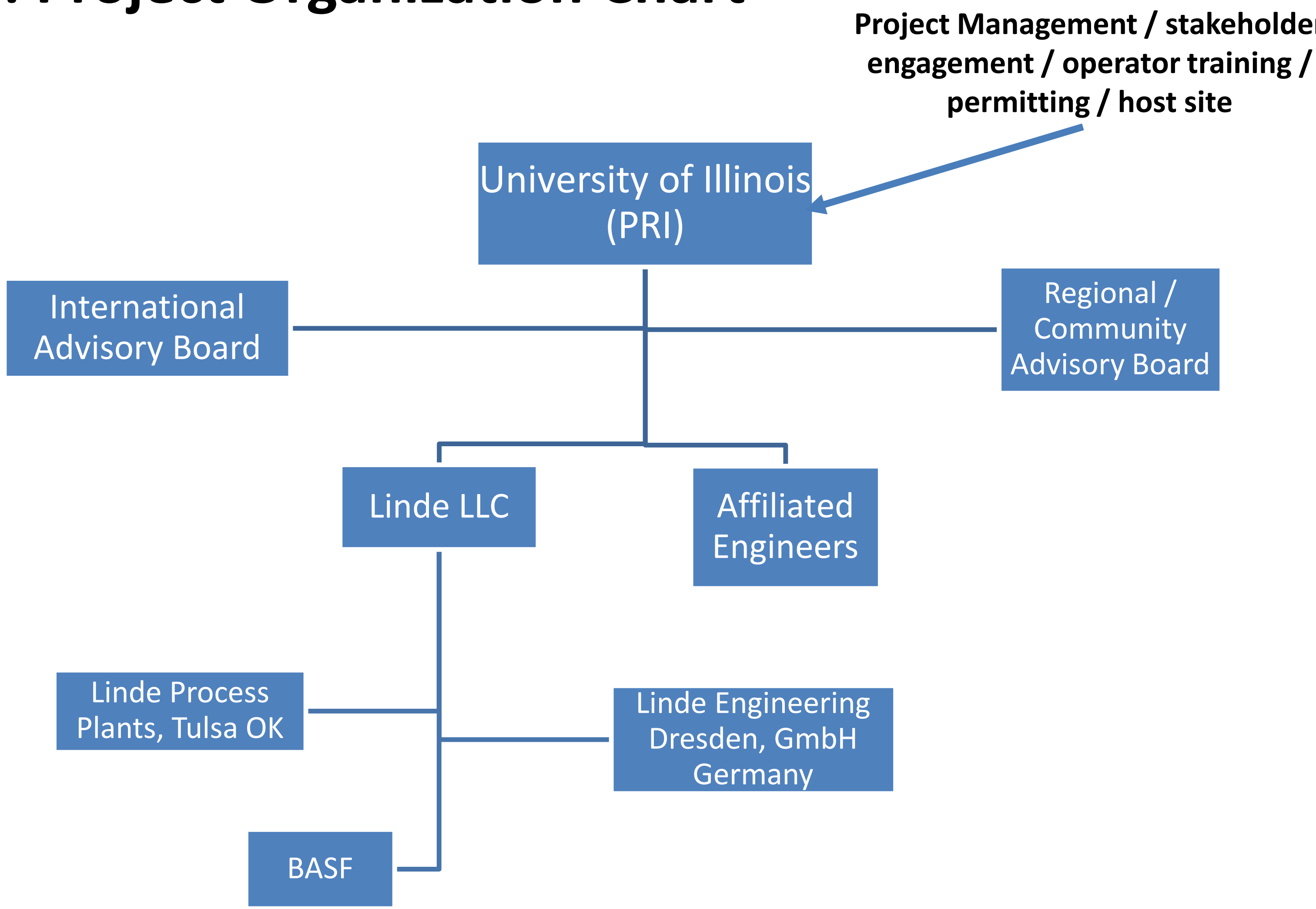

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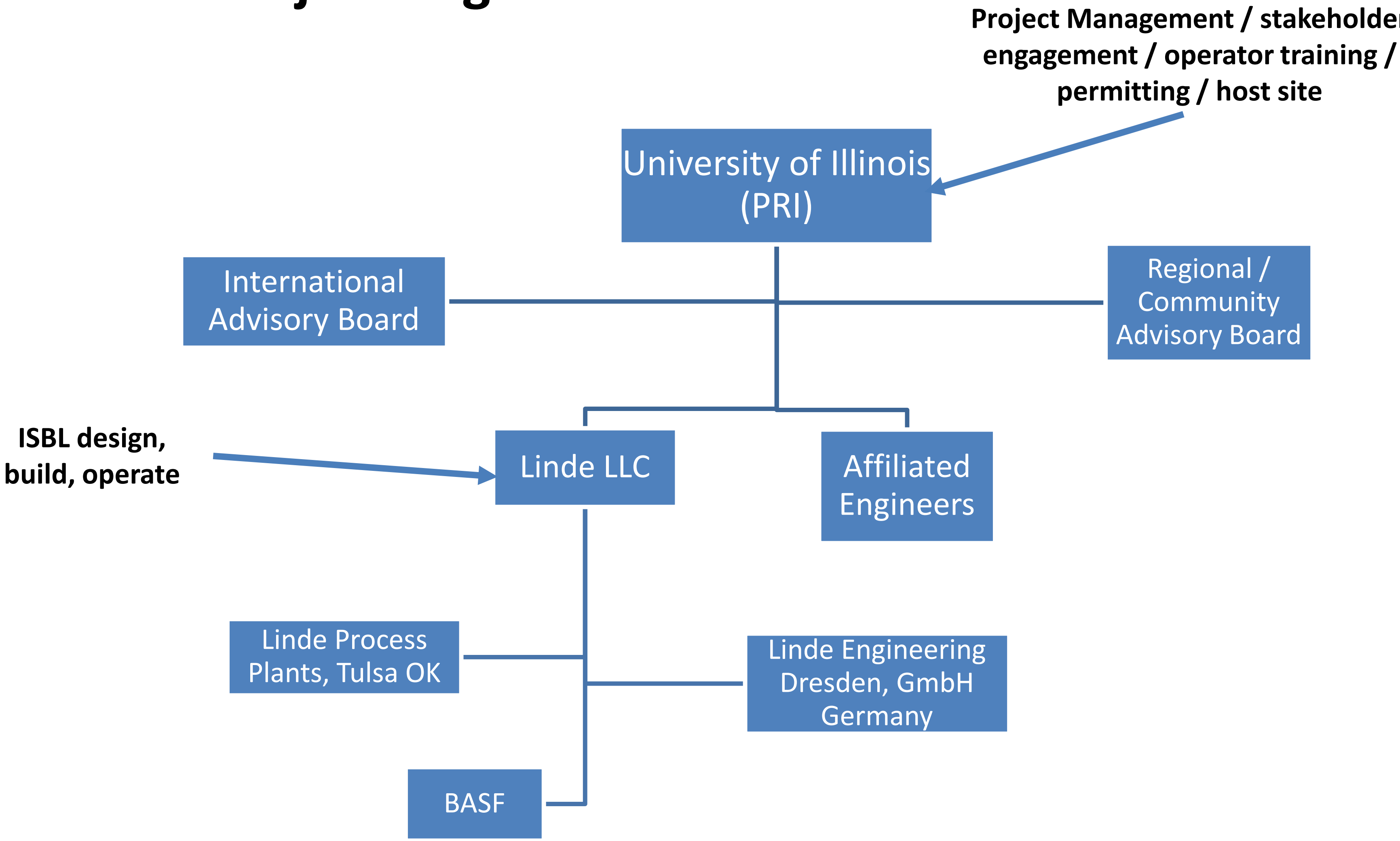

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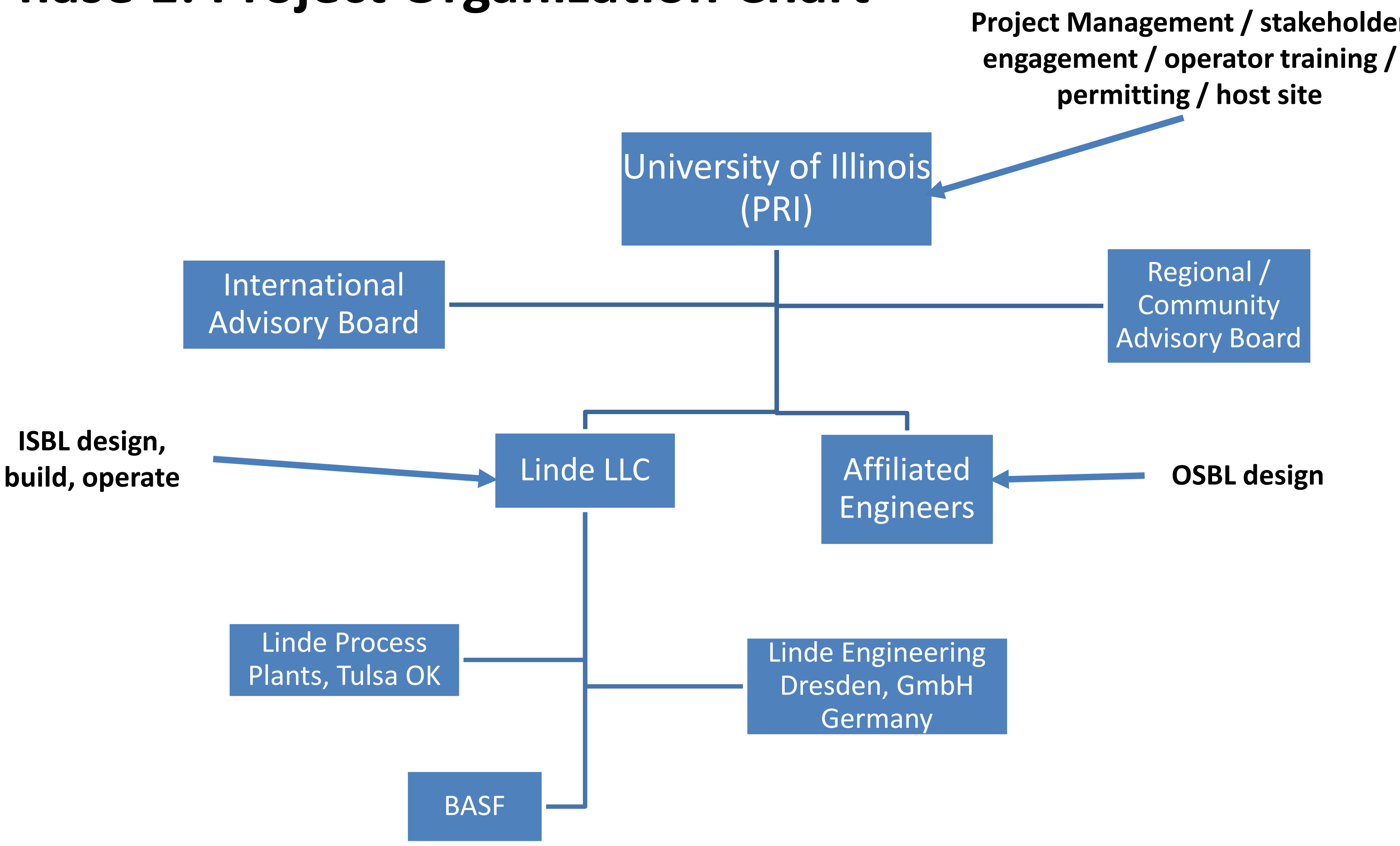

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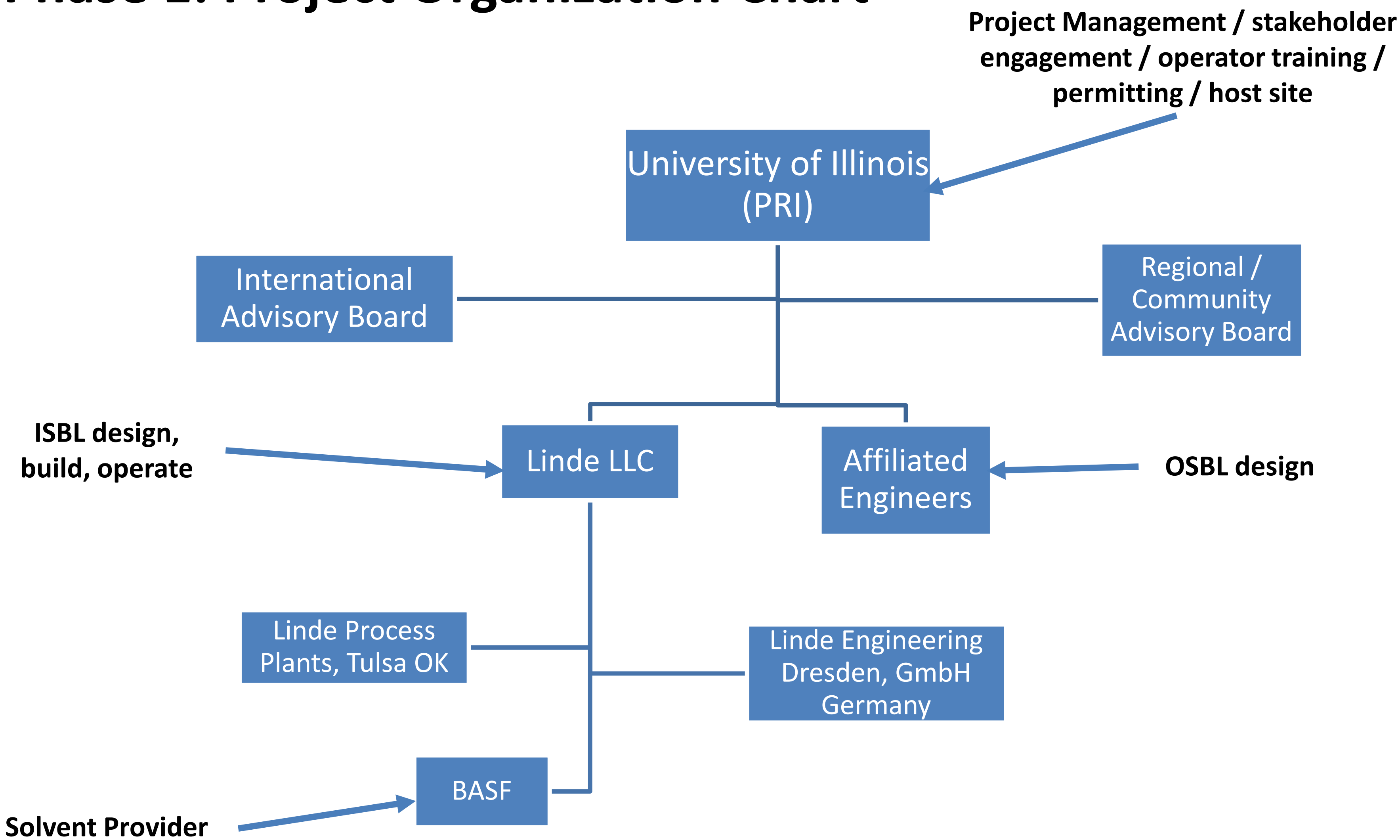

Advisory Board for Capture Project and Center

Key partnerships regionally and internationally

DBT-IOC
BIO-ENERGY RESEARCH CENTRE

ITAQ

एनटीपीसी
NTPC
A Maharatna Company

CITY WATER LIGHT AND POWER
SPRINGFIELD, IL

Association of Illinois Electric Cooperatives
Your Touchstone Energy® Partner

中国石化
SINOPEC
中石化石油工程设计有限公司
Sinopec Petroleum Engineering Corporation

US Army Corps of Engineers®
Engineer Research and Development Center

ILLINOIS GREEN
BUSINESS ASSOCIATION

浙江大學
ZHEJIANG UNIVERSITY

ILLINOIS EASTERN
COMMUNITY COLLEGES

Center for Community Adaptation

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Southern Illinois University Carbondale

華能國際電力股份有限公司
HUANENG POWER INTERNATIONAL, INC.

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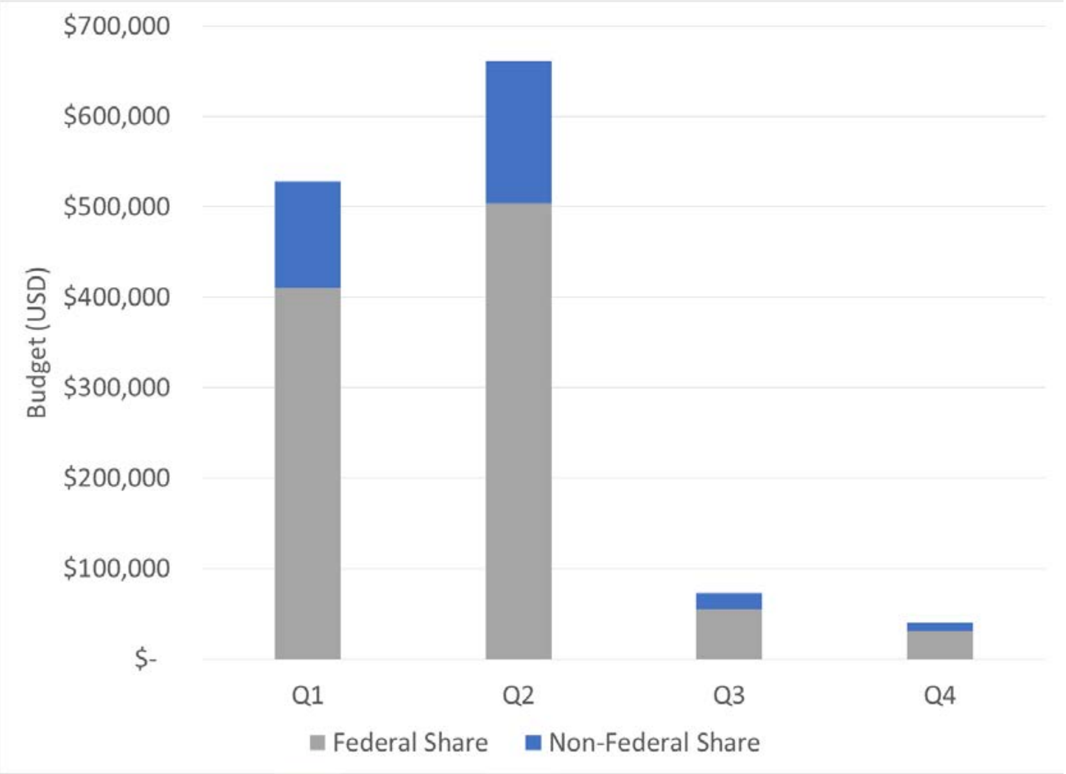
Project Performance: Dates and Funding

Financial commitment from all team members

BP1: OCT 1, 2015 TO SEPT 30, 2016

Source	Funding, $
DOE/NETL	1,000,000
University of Illinois	75,530
Linde LLC / BASF	166,566
Affiliated Engineers, Inc.	45,000
Assoc. of IL Electric Cooperatives	15,000
Total	1,302,096
Cost share	23%



Objectives

- Design and install a carbon capture system of nominal 15 MWe
  - Integrate with the Abbott Power Plant flue gas system
  - Demonstrate the viability of continuous operation under realistic conditions with high efficiency and capacity
  - Optimize the process at this scale and to gather performance data to enable a robust design of large commercial size plants
- Provide a guideline for the retrofit of other existing plants within the coal fleet
  - Enable future knowledge sharing with other utilities in order to encourage and facilitate the retrofit process
- Illustrate a path forward for the utilization of the captured CO_2

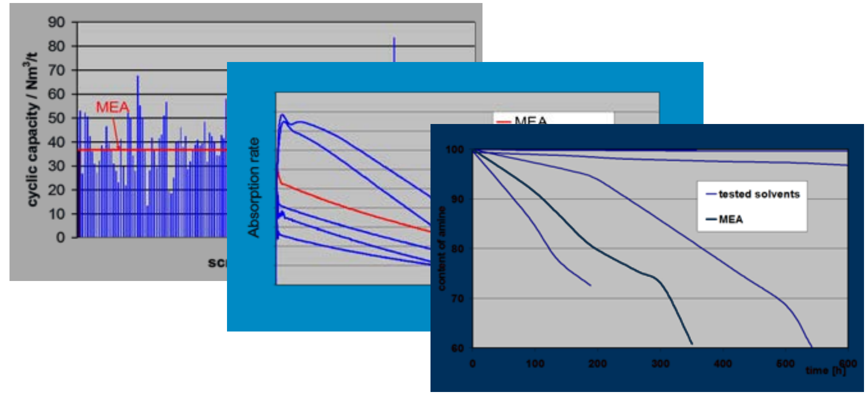
Successfully evaluated at the 1.5 MWe level at NCCC

TECHNOLOGY DESCRIPTION

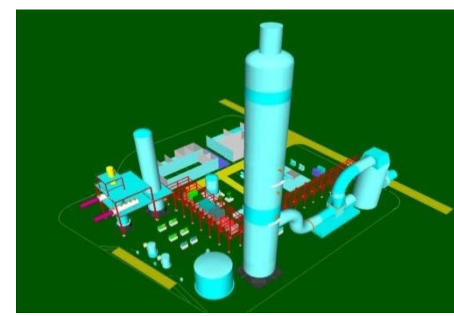
BASF OASE® Blue Technology Development

Adopted and Optimized for PCC Applications

- Equilibria
- Kinetics
- Stability

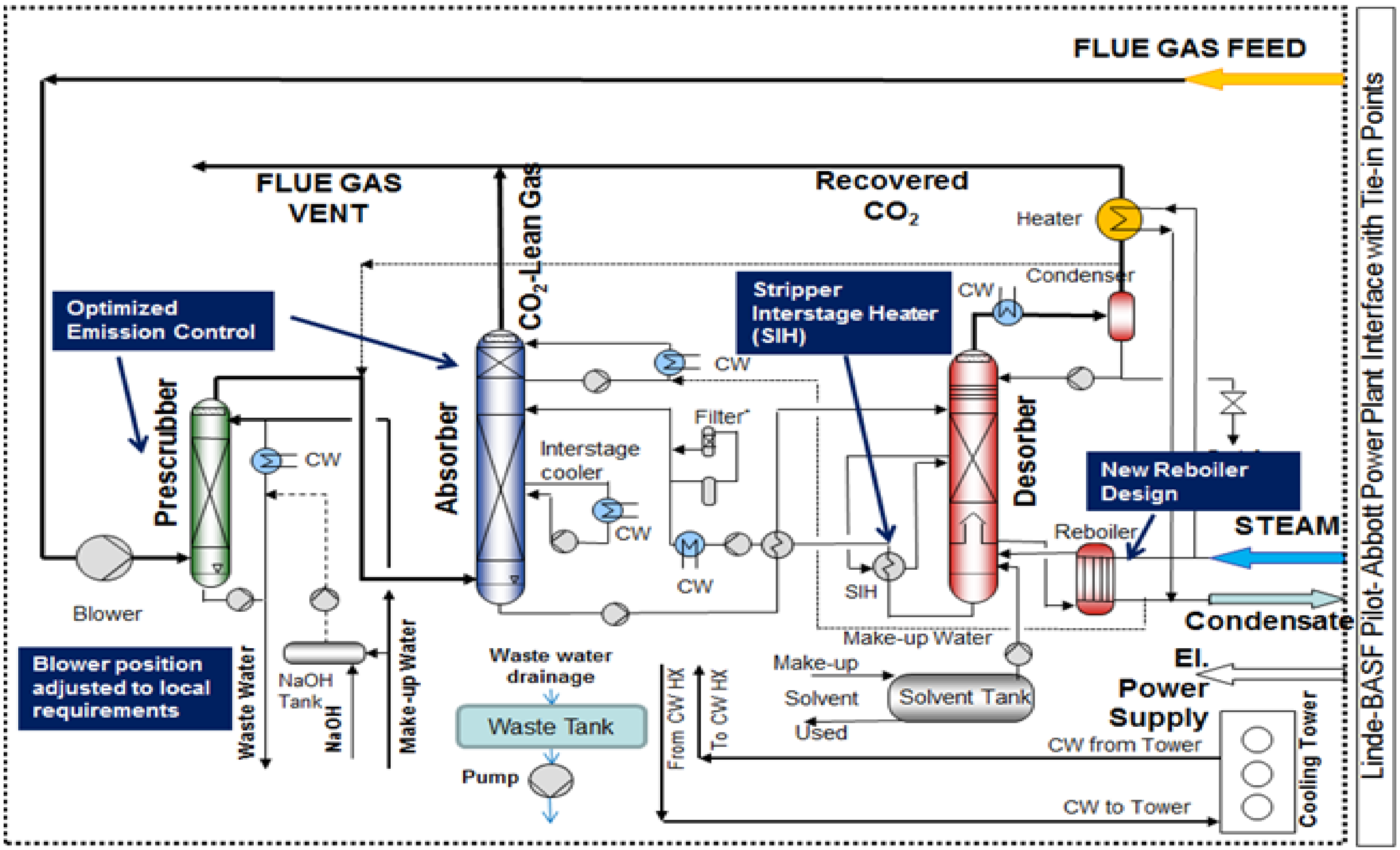


Mini plant	Pilot: 0.5MWe	Pilot: 1.5 MWe	Large Pilot: 15 MWe
— 2001, Ludwigshafen — Solvent performance verification	— 2009, Niederaussem — Process optimization, materials testing	— 2014, Wilsonville, AL — Design improvements, emissions confirmation	— 2016/20, proposed — PCC plant cost reduction — Full value chain



Overview of Capture System for Large Pilot Plant

Technology features



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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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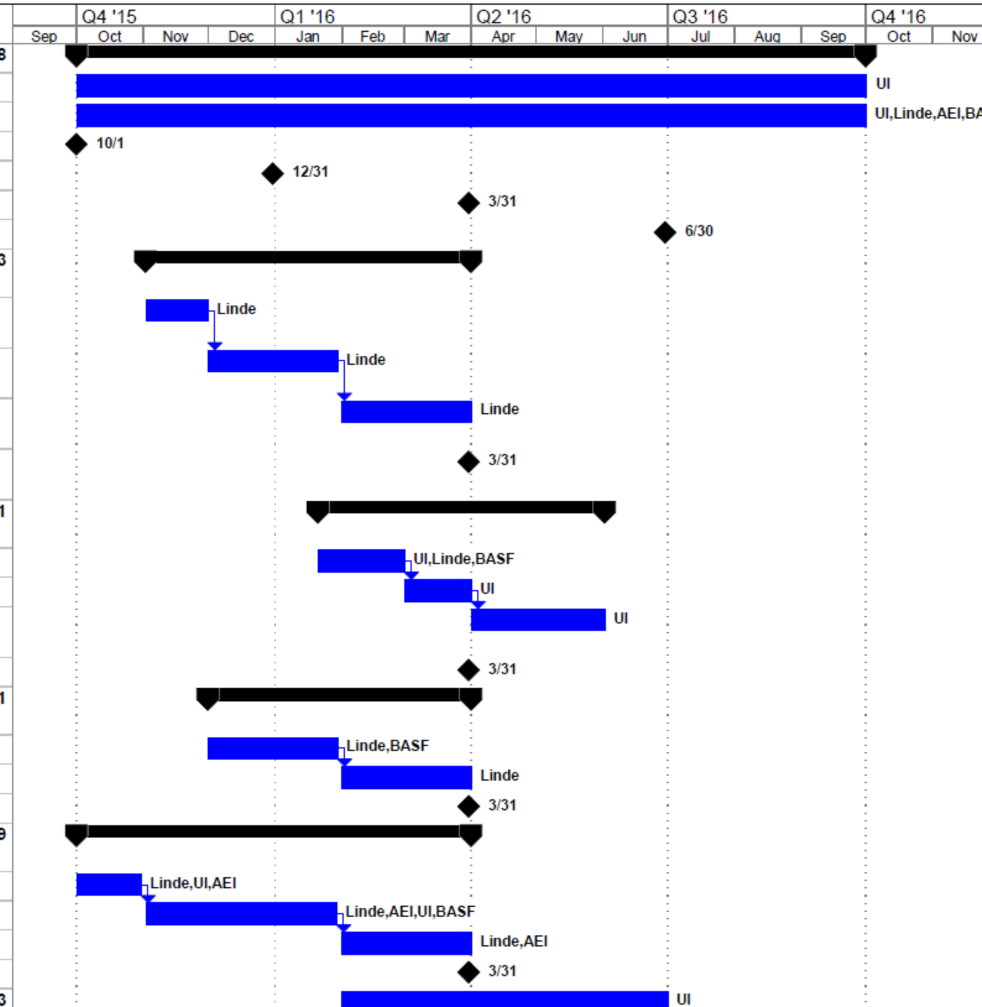
Executed on-time

TECHNICAL APPROACH / PROJECT SCOPE

Project Schedule, Tasks, and Milestones

Phase 1 effort

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 Accomplishments

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	4	Technology Gap Analysis 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	6/30/2016	Signed Agreement	Completed
1	6	Phase 2 Application Preparation Completed	3/31/2016 6/30/2016	3/31/2016 6/30/2016	Application Document	Completed

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Project Success Criteria

Decision Point	Date	Success Criteria
Go / No-Go Phase 2 Application	3/31/2016	Submission of continuation application
Negotiated and completed agreements	06/30/2016	Cost estimates for 15 MWe pilot meets targeted budget for funding and cost share in Phase 2
Go/ No-Go Phase 2 Initiation	10/1/2016	Phase 2 Award and commitment of funds for cost share

Steps in Building a Market for Captured CO_2

Combination of partnerships, technologies, and interest in economic development

- Find a Power Generator willing to host large scale pilot
  - Abbott Power Plant at University of Illinois
  - Traditionally evaluates new technologies and shares with other plants
- Assemble a "bondable" team with a proven capture technology (Phase I)
  - Linde/BASF provides proven technology
  - Linde/BASF; Affiliated Engineers Inc. experienced in large projects
- Obtain financing for project
  - Proposal to DOE for 15 MW large scale capture pilot
- Construct and test a large scale pilot system at the power generator (Phase II)
- Large scale pilot evaluations of technologies for utilization of captured CO_2 (Phase III)
  - Forming Center for CO_2 utilization
  - Capitalizes on 300 Tons/day of CO_2 generated

Phase 1 completed, milestones achieved, prepared for Phase 2

PROGRESS AND CURRENT STATUS

Overview of Phase 2 Project Schedule

More than just a design, build, operate project

BP2 (13 months)

- Basic Design/Engineering
- Detailed Design/Engineering
- Permitting Application
- EH&S Analysis
- Stakeholder Engagement

BP3 (17 months)

- Equipment & Materials Procurement
- Construction & Installation
- Permit Compliance
- Stakeholder Engagement

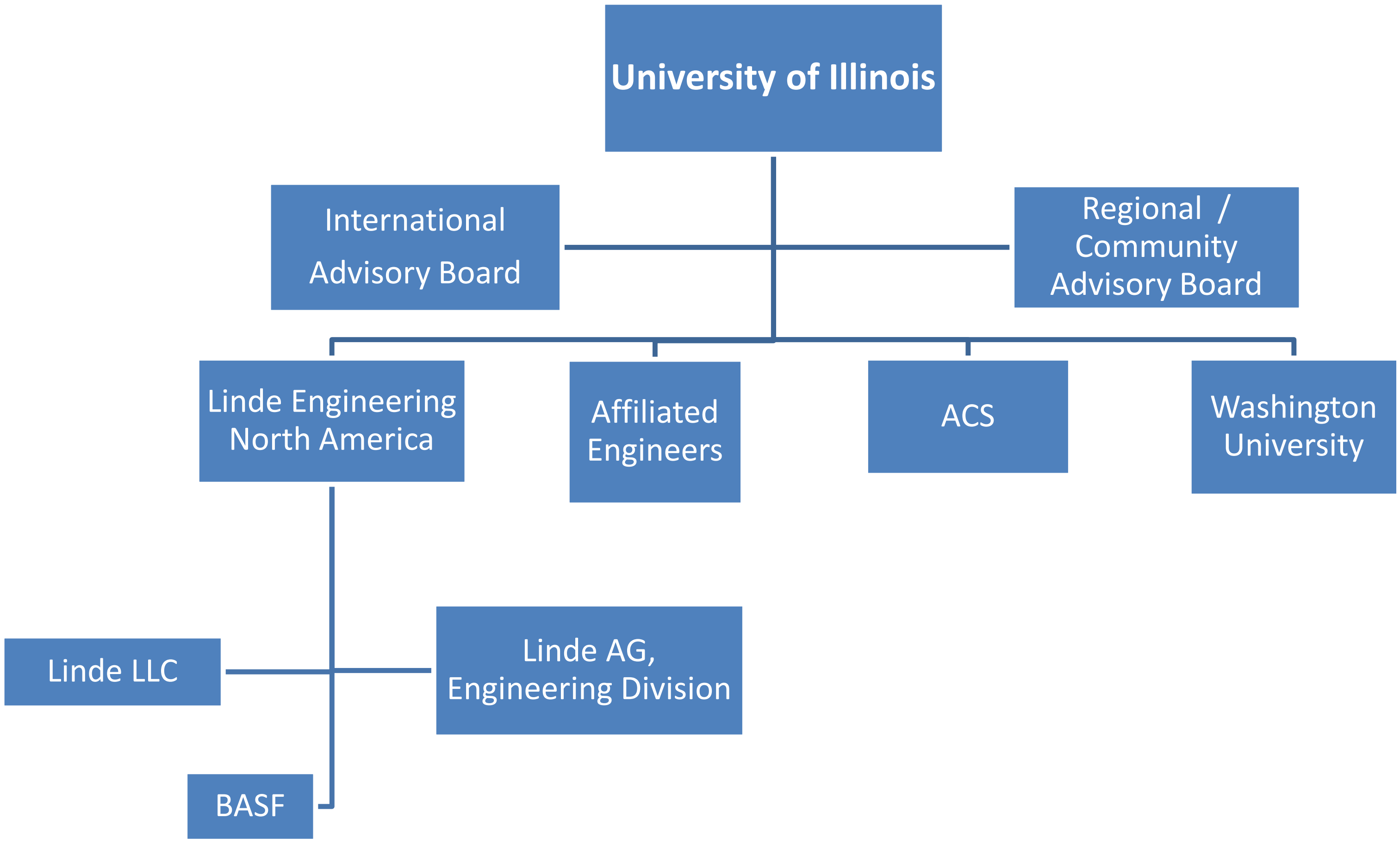
BP4 (18 months)

- Commissioning & Startup
- Pilot Plant Operation
- Testing Data Analysis & TEA
- Permit Compliance
- Stakeholder Engagement and Education Operations
- Commercialization Plan

- ***Stakeholder Engagement helps educate , understand market needs, and propagate technology***
- ***Education: workforce development for existing and future operators and engineers***
- ***Demonstrating not only the technology but how to create jobs and drive regional economies***

Phase 2: Project Organization Chart

Added expertise in aerosols, OSBL procurement / construction, and dry-bed emissions reduction



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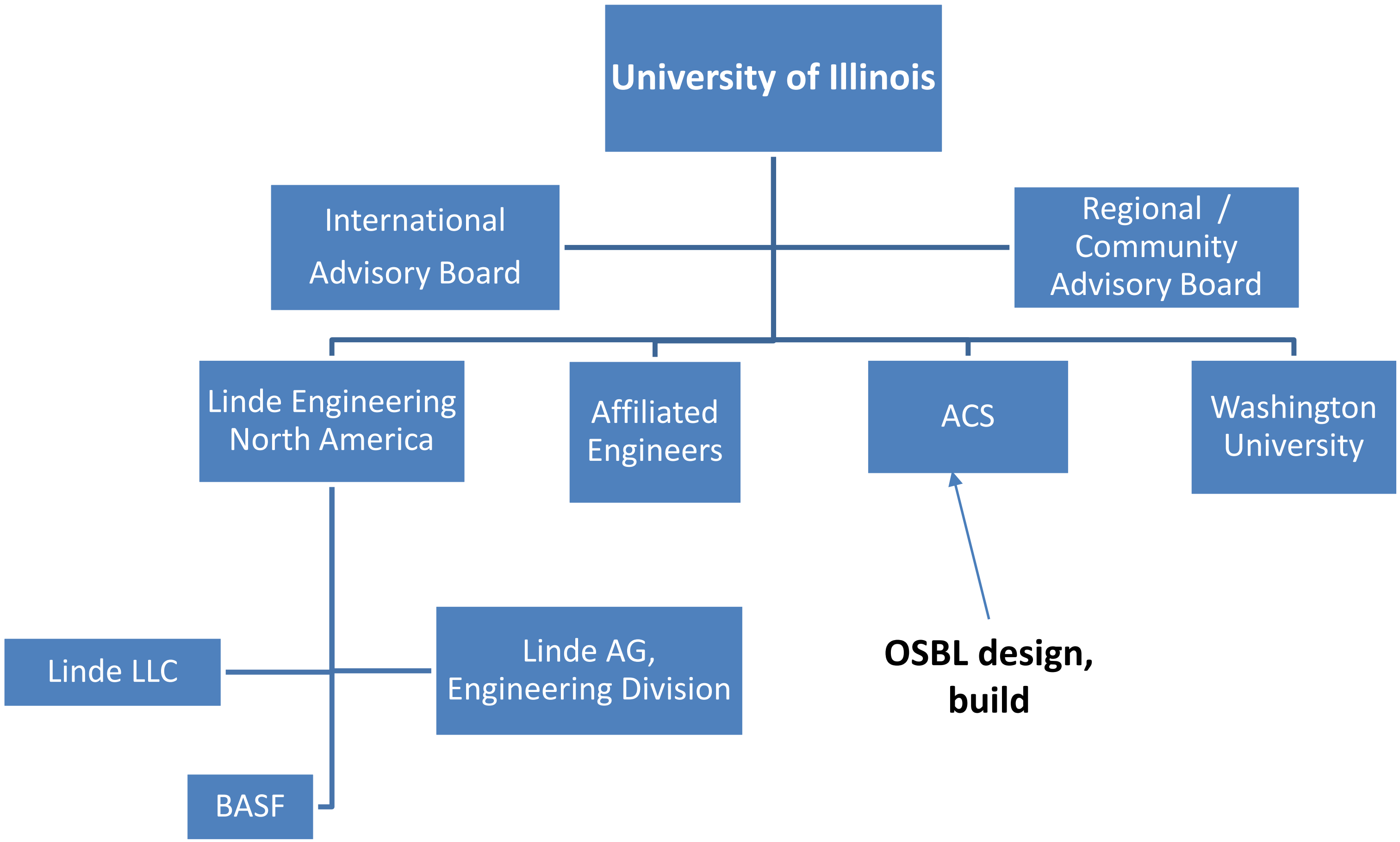

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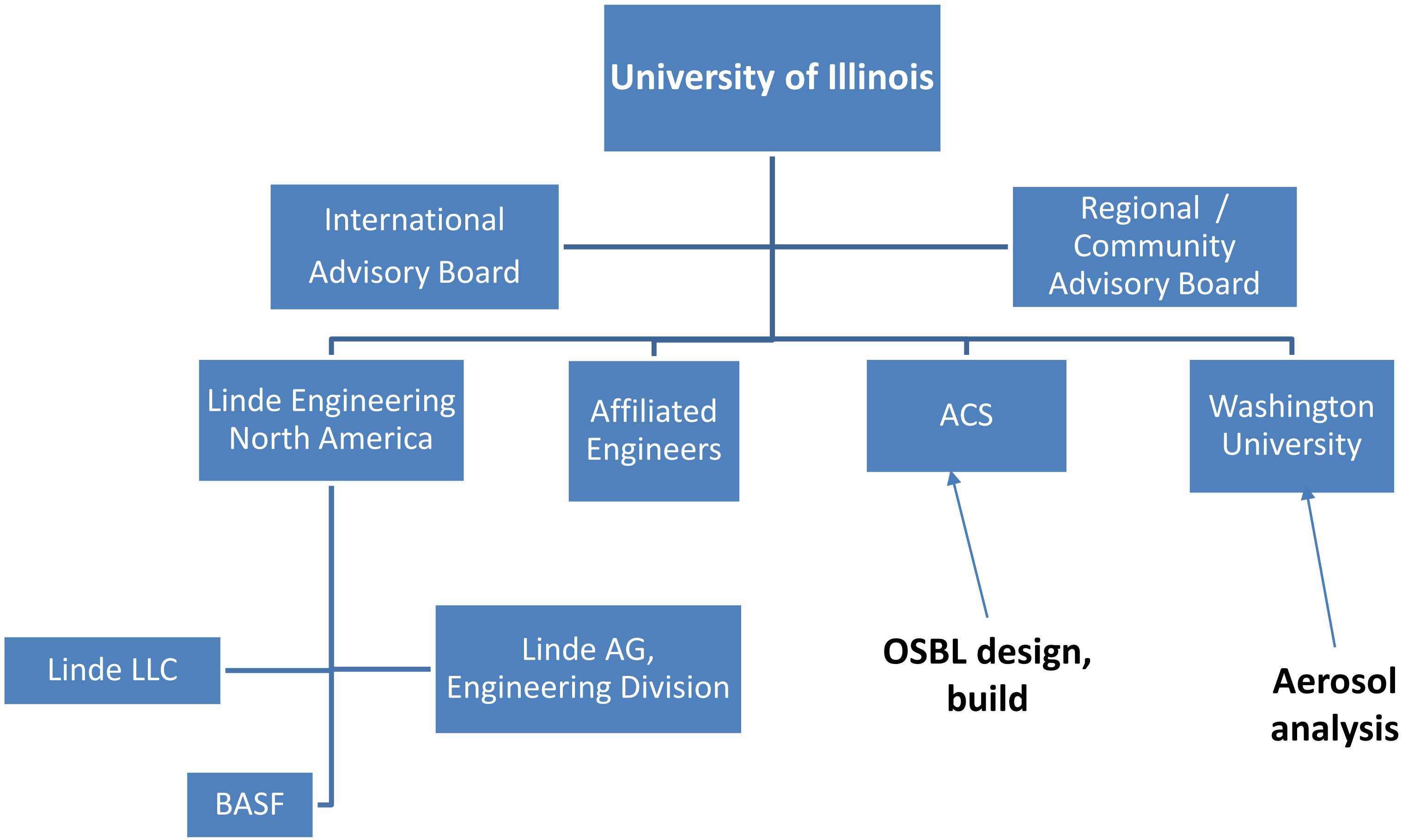

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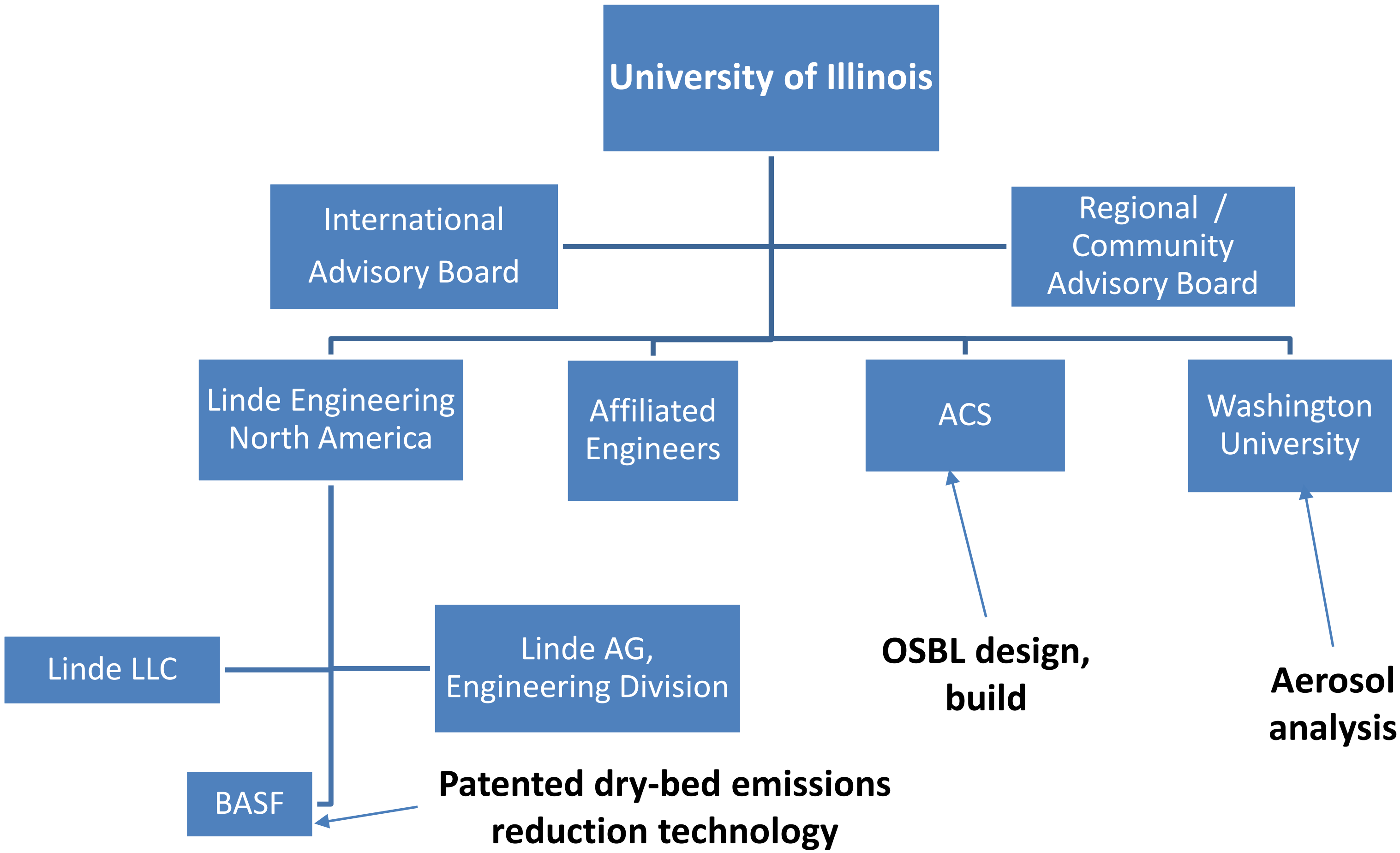
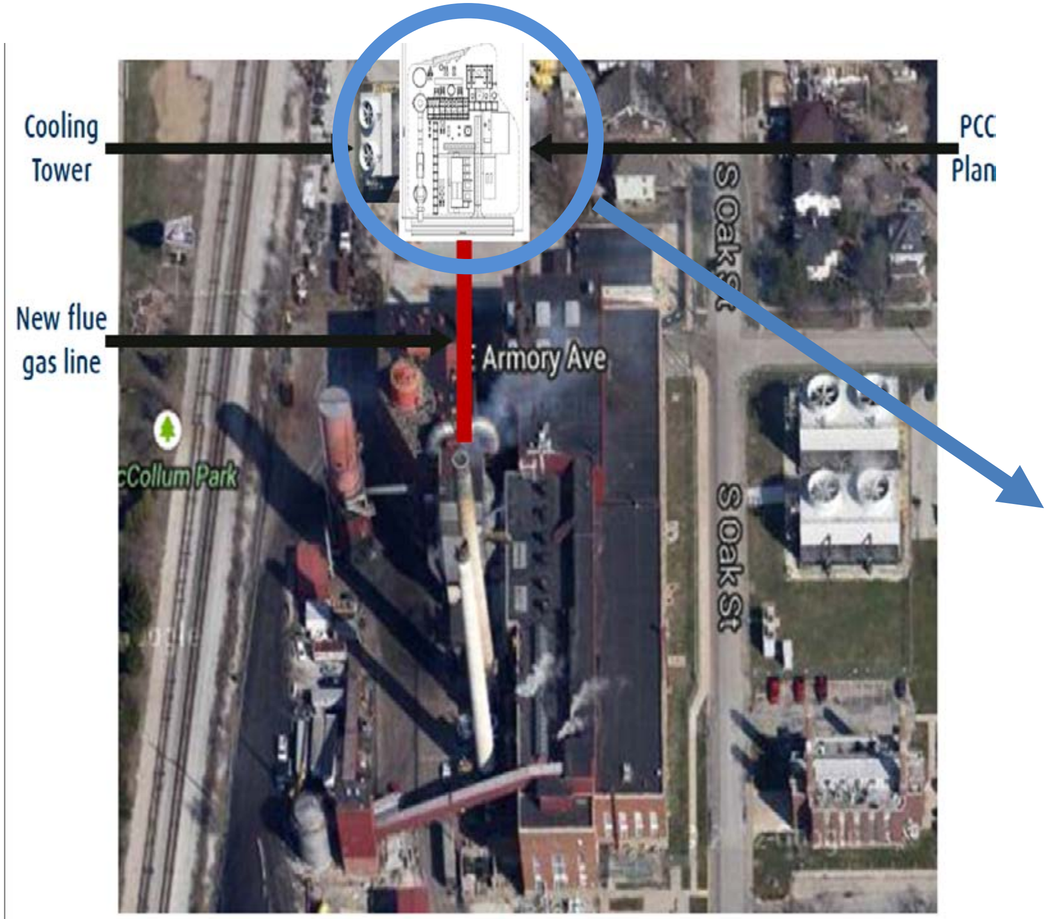
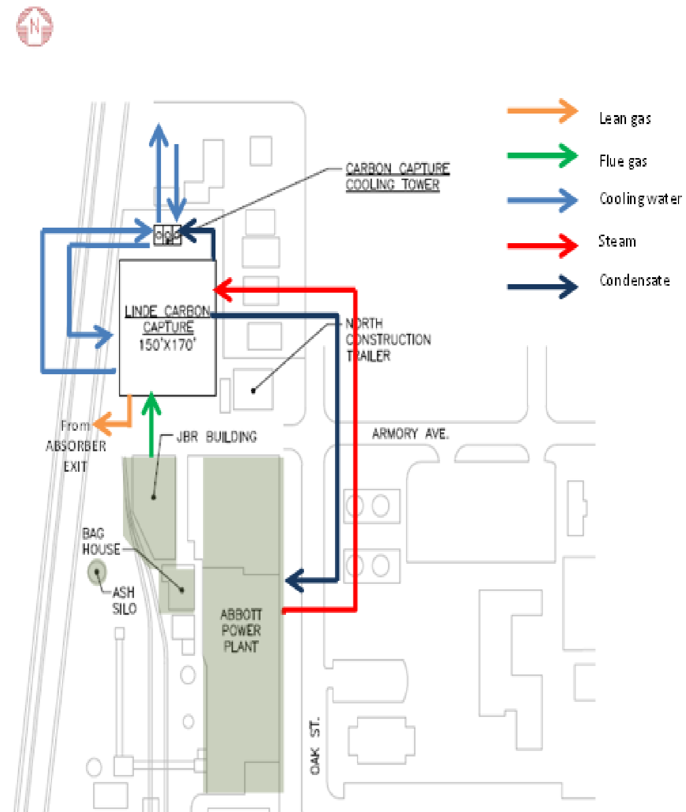


Task 5: Site for Carbon Capture Plant Established and Evaluated

Located close to Abbott Power Plant





Extract flue gas POST CEMS Unit

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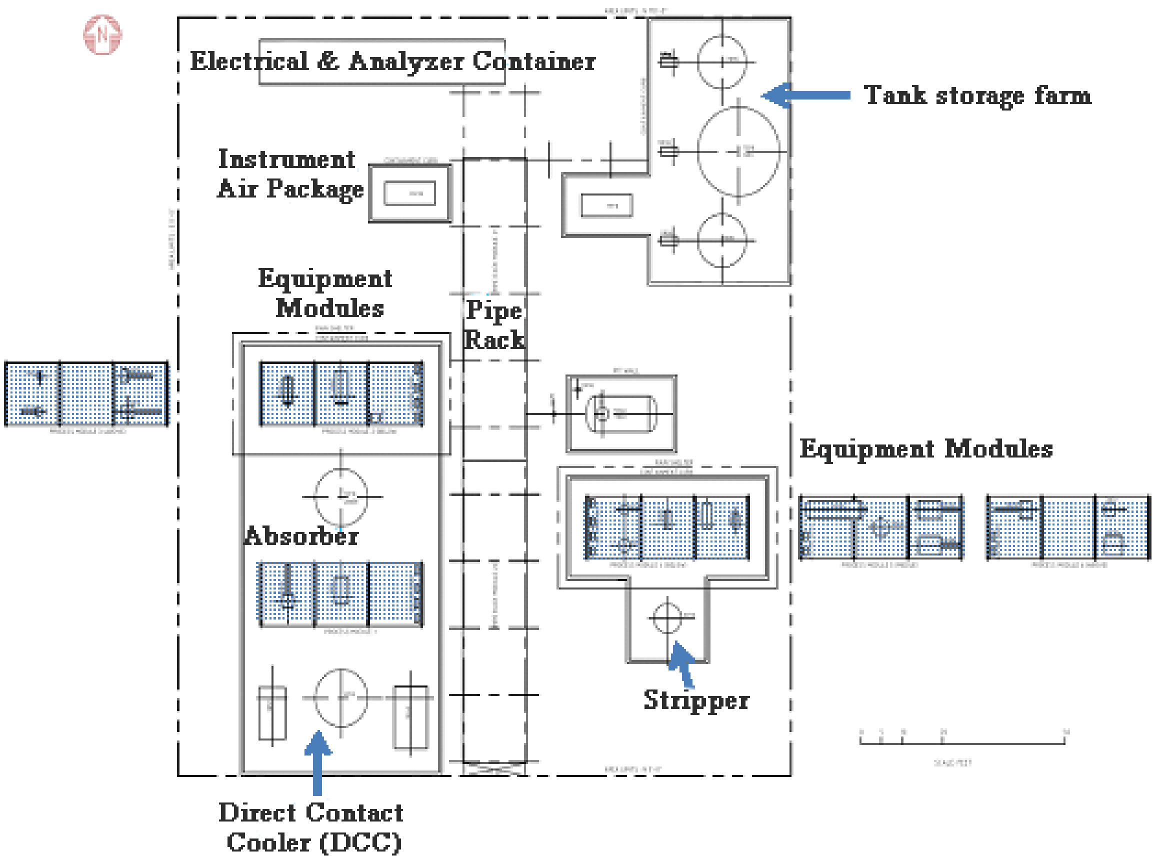
Task 5: Plot Plan for Capture Plant

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



Task 4: Technology Gap Analysis and Risk Mitigation

Technology Gap	Steps to Close Gap
Absorber Column design, size, scale-up	• Apply Linde commercial experience from past column designs • Assess low cost column construction • Experience from large scale pilot will contribute to knowledge for full scale plant deployments
Flue gas composition variability	• CO2 recycle from stripper to absorber emulates higher CO2 compositions in flue gas • Direct contact cooler to manage higher SO2 conc. In flue gas
Load following strategy and response	• Design load-following strategy for capture plant to enable fast response
Aerosol formation and solvent losses/carry-over	• Design, construct, test aerosol control module early in BP2 • Measure particles and amine carry-over
Stripper interstage heating and advanced flash stripper	• Reduce reboiler duty by incorporating stripper interstage heating • Weigh reduction in energy consumption vs capital costs
Solvent Management	• Assess solvent recycle options • Test portable solvent reclaiming system • Develop solvent delivery and storage options using BASF's experience in other amine solvent applications
Water & wastewater management	• Evaluate Reverse Osmosis option to treat blowdown water and reuse • Evaluate makeup water softening options • Evaluate the use of blowdown water from Abbott's cooling towers • Evaluate the use of flue gas condensate from DCC as process water

Task 3: Environmental Health & Safety Risk Mitigation

Safety & H 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 downs • 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.

Task 3: Permitting Strategy

Illinois EPA: air and water

	Air	Water	
Permit Type	Construction	Construction Storm Water	Water Pollution Control
Agency	Illinois EPA	Illinois EPA	Illinois EPA
Time for Processing	6-9 months	3-5 months prior to construction	90 days
Duration	Valid for 12 months of construction, with possible extension	N/A	N/A
Operation	Covered under construction permit	Covered under construction permit	N/A
Fees	Up to $10,000	$250-$750	TBD
Issues	Increased utilization; stakeholder concerns	Stakeholder concerns	TBD

Task 3: Permitting Strategy

UCSD: Local sanitary district

Permit	Connection Permit
Agency	Urbana & Champaign Sanitary District (UCSD)
Time for Processing	Up to 1 month after IEPA Water Pollution Control Permit
Operation	N/A
Fees	• Connection Fee: $325/100 gallons* • Interceptor Cost Recovery Fee: $325/100 gallons* • Base user Fee: $0.6042/100 cf + User Surcharge – pretreatment credit (monthly charge based on actual volume and quality of discharge
Issues:	UCSD concerned about organic contaminants, heavy metals, ammonia
* anticipated May 2017 rate	

Task 2: Process Performance and Cost Summary 550 MW

Utilizing Illinois No. 6 Coal

Table 4. Process performance and cost summary for DOE/NETL cases compared to Linde-BASF technologies

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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Plans for Future Testing/ Development/ Commercialization

PHASE III AND PROGRESS TOWARDS MARKET FORMATION

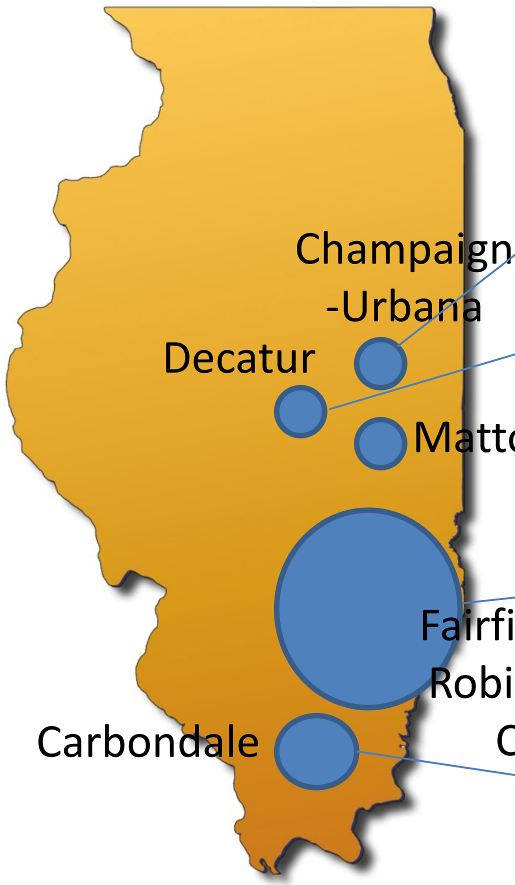
Phase III: Center for CO_2 Utilization

Forming center to address market needs

- Goal: Bring together university researchers and industry partners to examine large scale pilots to UTILIZE the captured CO_2
- Looking for partners throughout the value chain, i.e. CO_2 users and CO_2 generators
- Looking for international partners willing to test large scale systems and share information
- Will include educational and workforce development components
- Developing research thrust areas now

Regional & Global Test Bed for CCUS

Concentration of natural resources and intellectual capital



- Capture of CO_2 : Abbott Power Plant UI
- Storage of CO_2 : ADM Project
- Utilization of CO_2 : Enhanced Oil Recovery (EOR)

Illinois Eastern Community Colleges

- Operator Training

- Coal combustion

ACKNOWLEDGEMENTS

Name	Organization
Bruce W Lani	National Energy Technology Laboratory / US Department of Energy
Yongqi Lu, Vinod Patel, Hong Lu, Sallie Greenberg, Randy Locke, Deb Jacobson, Gary Miller	Prairie Research Institute / University of Illinois
Michael Larson, David Wilcoxen, Richard Rundus, Tracy Malvestuto	Abbott Power Plant / University of Illinois
Krish Krishnamurthy, Makini Byron, Joseph Naumovitz, Torsten Stoffregen, Ali Jangi, Andy Poplin	Linde
Sean Rigby	BASF
David Guth, Steve Bennett	Affiliated Engineers Inc.
Steve Davis, John Lowrey	Association of Illinois Electric Cooperatives

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