Engineering Design of a Linde-BASF Advanced Post-Combustion CO_2 Capture (PCC) Technology at a Linde Steam Methane Reforming H_2 Plant

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Acknowledgement and Disclaimer

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Project Overview

- Project cost $1.969 MM: DOE funding $1.5 MM; Linde cost share $0.469 MM
- Project duration: 18 months (October 2020 to March 2022)
- Project participants:

Project Objectives

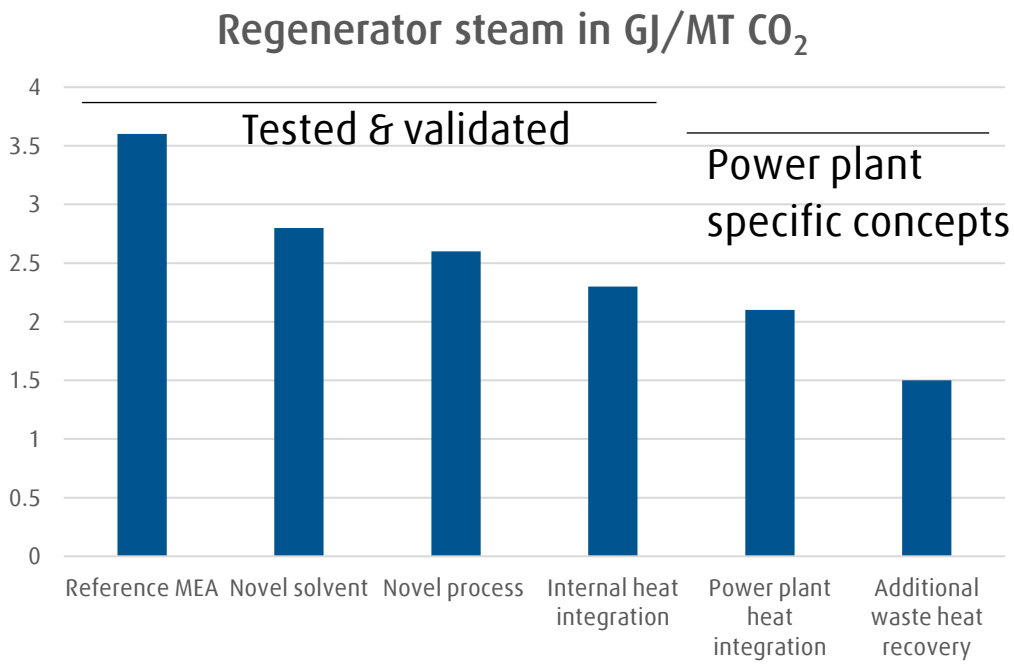
- Engineering design of a Linde-BASF advanced post-combustion CO_2 capture technology at the H_2 Plant
- Site-specific engineering study to create a strong foundation to pursue a commercial project
  - Capture 90% of CO_2 from SMR flue gas and compress to 2200 psia
  - Estimate CAPEX and OPEX and perform technoeconomic analysis to determine CO_2 capture cost

Technology
Linde-BASF Post-Combustion Carbon Capture (PCC) Technology

- OASE® blue solvent
  - Tolerance to O_2 and FG impurities
  - Favorable kinetics and reduced steam energy requirements
  - Demonstrated solvent stability
  - Lower solvent circulation rate
  - Minimal solvent losses
- Technology tested from 2009-2017 in two pilot plants
  - Different flue gas sources
  - Wide range of flue gas compositions and impurities
  - Achieved Technology Readiness Level of 6
  - Multiple process design improvements achieved
- Scale-up
  - 30 Ton/d demo at Wilsonville, AL on coal flue gas in 2015-16
  - 250 Ton/d to be built at U. of Ill. 10 MW coal power plant in Springfield, IL

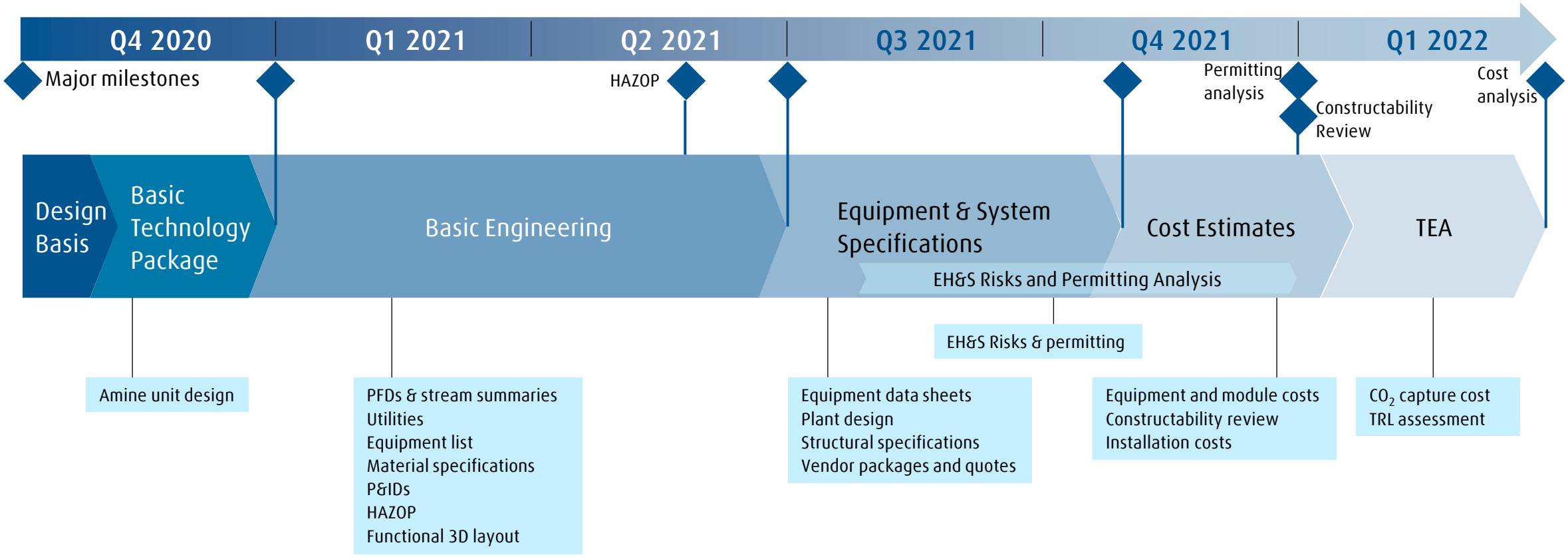
Technology
Progress of Continuous Improvements To Date

Reducing low pressure steam consumption:



- Capex reduction:
  - High-capacity structured packing (smaller diameter absorbers)
  - Higher pressure regeneration (Reduced CO_2 compressor cost)
  - Novel lower cost equipment (e.g., reboiler, inter-stage heater)
- Electrical energy reduction:
  - CO_2 compression power by operating at higher regenerator pressure
  - Reduced solvent recirculation flow
- Other features for lower OPEX:
  - Reduced solvent inventory
  - Fast dynamics for load following

Technical Approach & Major Milestones



Project Success Criteria

Decision Point	Date	Success Criteria
End of Project goal	03/31/2022	Cost estimate completed for CO2 capture and compression plant from SMR with accuracy of +/- 25%

Progress Update
Host Site Selection

- Selected one of the largest SMR plants from Linde's Gulf Coast fleet
  - Sufficient space available adjacent to existing SMR
  - Sufficient capacity for additional utilities
- 400+ miles of pipeline network connects multiple plants and customers
  - Includes H_2 storage cavern
- Proximity to CO_2 sequestration sites
  - Saline aquifers
  - Depleted oil and gas fields
  - Large storage capacities for >20 years operation

Linde's large SMRs in the US Gulf Coast

sedimentary basins
sedimentary rocks more than 800m thick
faults
footprint of trapped CO_2
array of injection wells
16 storage capacity (billion metric tons of CO_2)

Progress Update
Design Basis

- Plant concept
  - Single train design with one DCC (direct contact cooler), single train amine unit with one absorber and one regenerator, one CO_2 compression train
  - Minimal impact on SMR operation due to integration of PCC
- CO_2 capture capacity is ~1.4 million tonnes/year

Feed - SMR Flue Gas	
Temperature, F	~320
Pressure, psia	14.7
Composition (mol%)	
N_2 + Ar + O_2	~62%
CO_2	~18%
H_2O	~20%
Trace impurities	< 100 ppm

CO_2 Product Specifications	
CO_2 purity	>95%
Temperature, F	<120 F
Pressure, psia	2200
Water	< 630 ppm
Oxygen	<10 ppm
Nitrogen	<4%

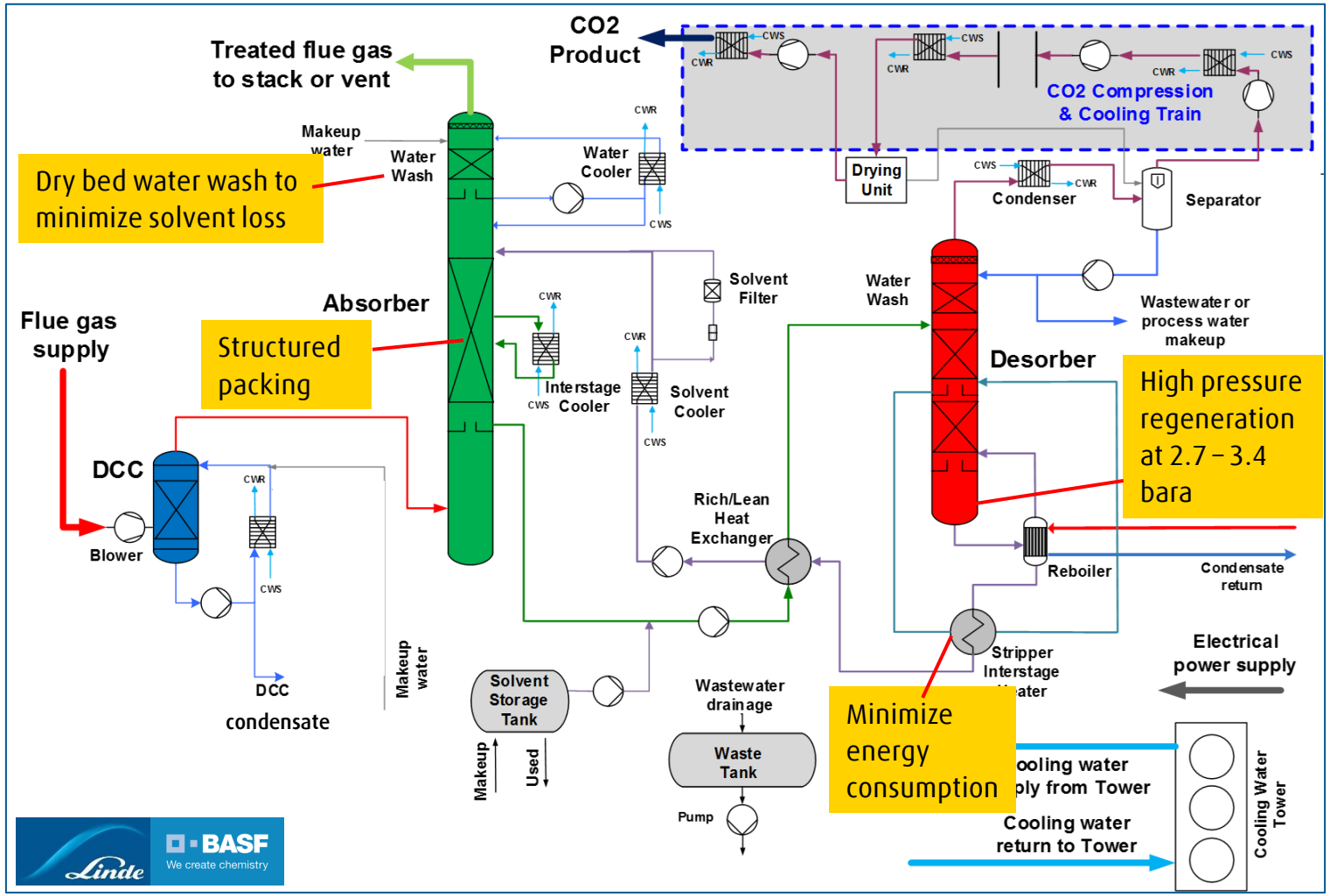
Progress Update
Basic Technology Package

- BASF developed 90% and 95% CO_2 capture cases
  - Preliminary sizes of major equipment such as absorber, stripper, solvent pumps, heat exchangers were provided
  - Specific reboiler duties were estimated

- 95% capture case was selected based on the following
  - Incremental specific energy consumption was small at ~1.5% compared to 90% case
  - Both cases required single train design
  - Incremental absorber/stripper diameters for higher capture rate were minimal
  - Specific Capex per unit volume of CO_2 is likely lower due to economy of scale

- CO_2 purity of >99.9% (by vol. on dry basis) well exceeds the purity specification

Progress Update
Process Design

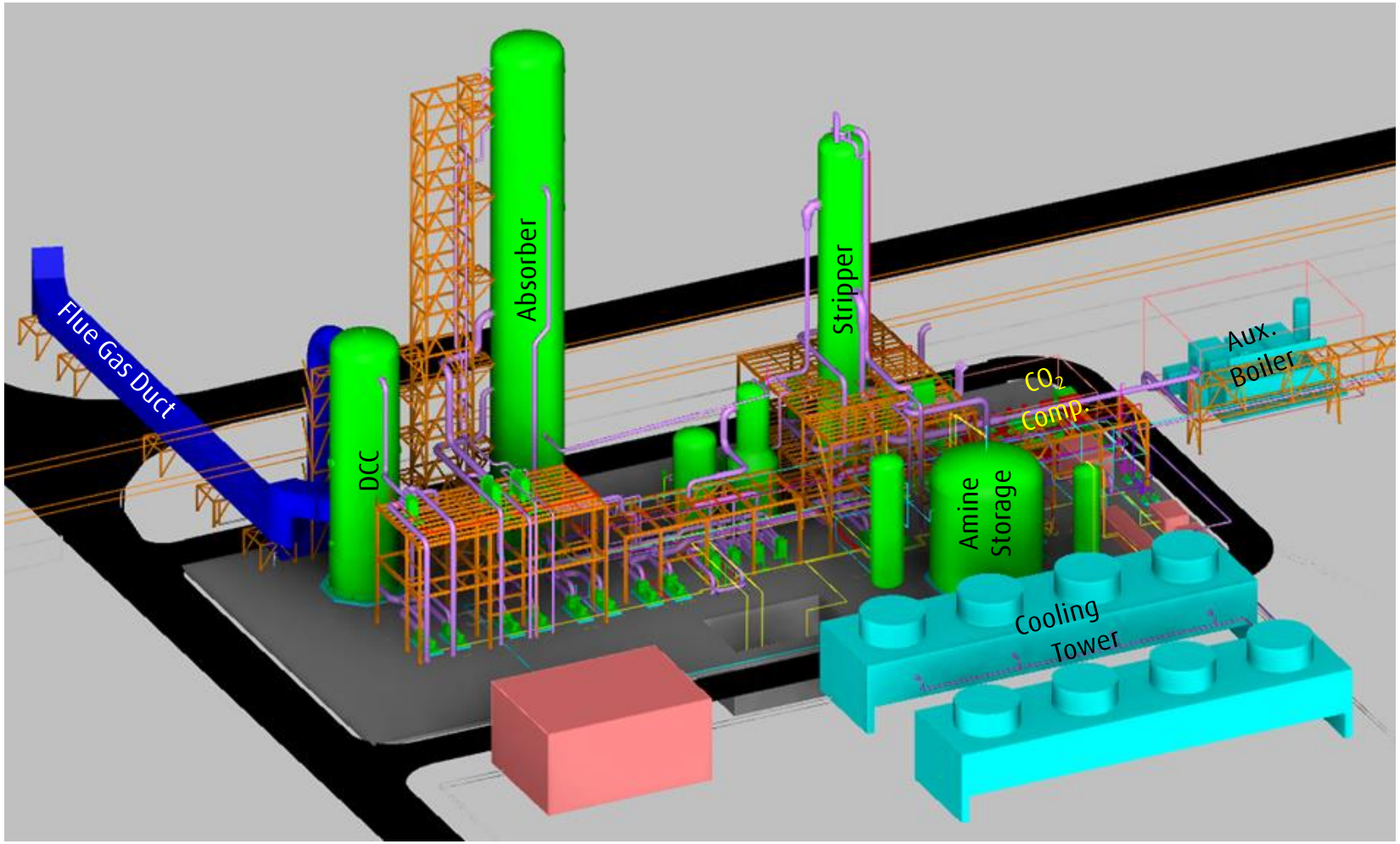


- Key features
  - 95% CO_2 capture rate
  - Reboiler duty ~2.6 GJ/tonne
  - Minimal solvent loss to atmosphere
  - No amine disposal required with the use of reclaimer
  - Structured packing in absorber
  - Compression train with chiller to meet moisture specs
  - Maximized wastewater recycle

Progress Update
Basic Engineering

- Completed Deliverables
  - Equipment list
  - Process data sheets
  - P&IDs
  - Analytical requirements
  - Electrical load list
  - Plant and environmental safety concept
  - Material specifications, and
  - Functional 3D layout of the plant
- HAZOP
  - No major design flaws were identified
  - Team identified several improvements to be incorporated into design to make it inherently safer
  - P&IDs have been updated based on HAZOP actions

Progress Update
Basic Engineering – 3D Layout



Major Project Risks and Mitigations

Risks Addressed To Date	Mitigations
Host site initially proposed was unavailable	Alternative site from Linde's SMR fleet was identified and confirmed by Business as a suitable site
Integration with operations at SMR plant	Engaged internal experts intimately familiar with the selected SMR
Unavailability of utilities for capture plant	Host site confirmed capacity for providing additional utilities needed for the capture plant
Large volumes of process condensate from DCC	Identified suitable reuse within the plant
Safety issues arising from improper design	HAZOP was completed to make the design inherently safer
Little to no commercial opportunity for CO_2 offtake	Companies interested in CO_2 offtake have already been identified
Remaining Potential Risks	**Mitigations**
Permitting requirements add project complexity/ cost	Detailed permitting analysis is planned to determine cost and schedule for new permits as well as impact on existing permits
Cost/schedule risks	Frequent reviews of availability of resources and budget forecasts Proactive actions for alternative resources and cost efficiency

Summary

- Host site selected with proximity to multiple sequestration sites
- Capture capacity of ~1.4 MM tonnes/yr
- Linde worked with BASF to develop the basic technology package
- 95% Capture case is selected for the engineering study
- Basic engineering has been completed
- Efforts are now focused on analyzing permitting requirements and developing EPC cost estimates
- Project remains on track for successful completion by Q1 2022

Thank you for your attention.

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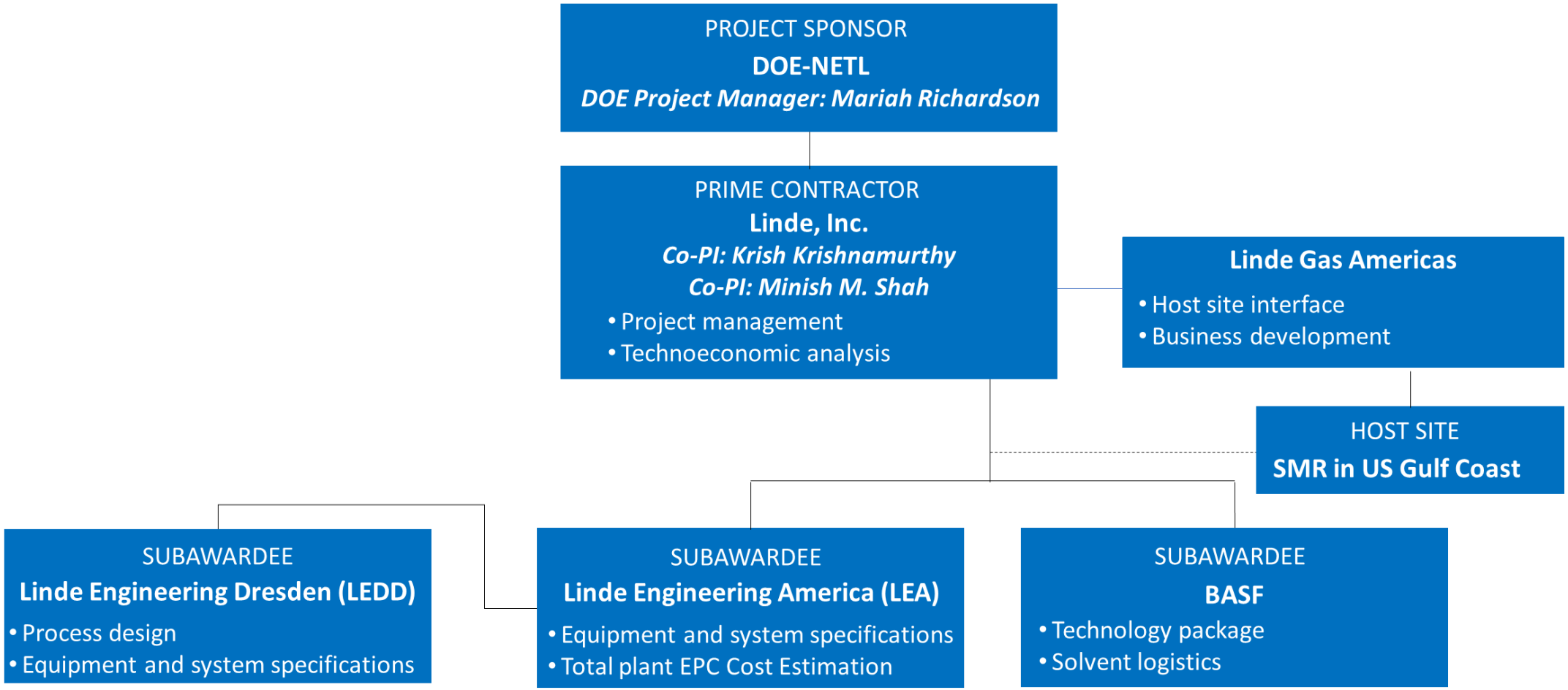
Project Organization Chart



Project Gantt Chart

WBS	Task Name	Start	Finish
1	**Project Management**	**Thu 10/1/20**	**Thu 3/31/22**
1.1	Project Management	Thu 10/1/20	Thu 3/31/22
1.2	Technology Maturation Plan (TMP) Analysis	Thu 10/1/20	Thu 3/31/22
2	**Engineering Design Study**	**Thu 10/1/20**	**Fri 10/29/21**
2.1	Basic Design	Thu 10/1/20	Thu 12/31/20
2.2	Basic Engineering	Thu 10/1/20	Wed 6/30/21
2.3	Equipment and System Specification	Thu 4/1/21	Fri 10/29/21
3	**Safety and Environmental Analysis**	**Fri 1/1/21**	**Thu 3/31/22**
3.1	Hazard and Operability Study (HAZOP) Review with Host Site	Fri 1/1/21	Mon 5/31/21
3.2	Environment, Health, and Safety (EH&S) Analysis and Permitting Analysis	Tue 6/1/21	Thu 3/31/22
4	**Cost Estimate Analysis and Commercialization**	**Fri 1/1/21**	**Thu 3/31/22**
4.1	Constructability Review	Wed 9/1/21	Fri 10/29/21
4.2	EPC Cost Estimation	Mon 11/1/21	Thu 3/31/22
4.3	Techno-Economic Analysis (TEA)	Fri 1/1/21	Thu 3/31/22