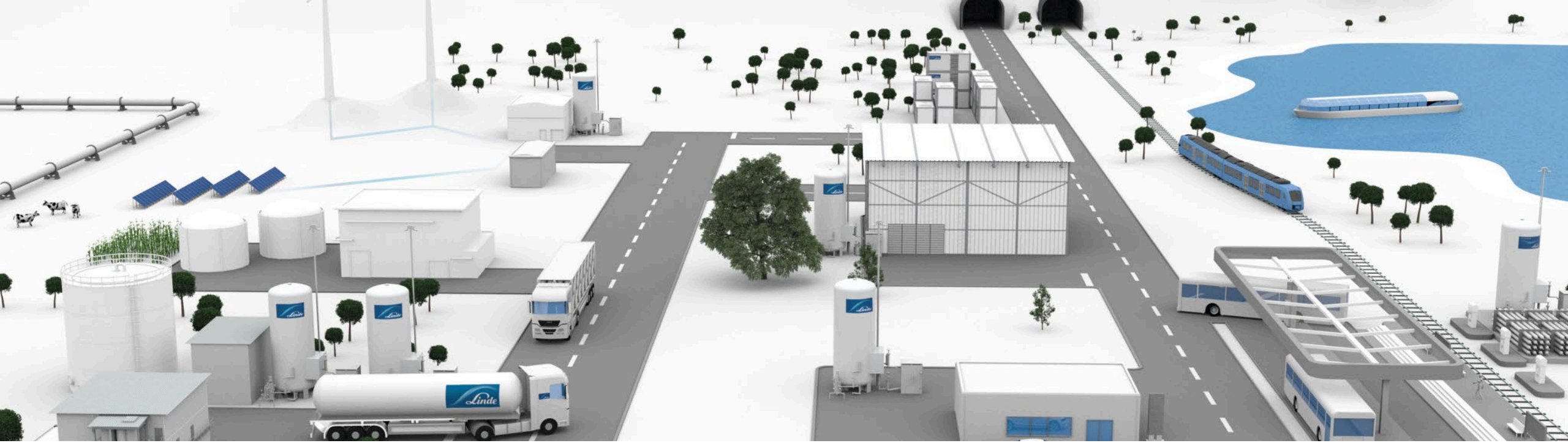

Engineering Design of a Linde-BASF Amine Technology for H_2 Plant Flue Gas

DOE Award No. DE-FE0031943

Minish M. Shah
Linde Inc.
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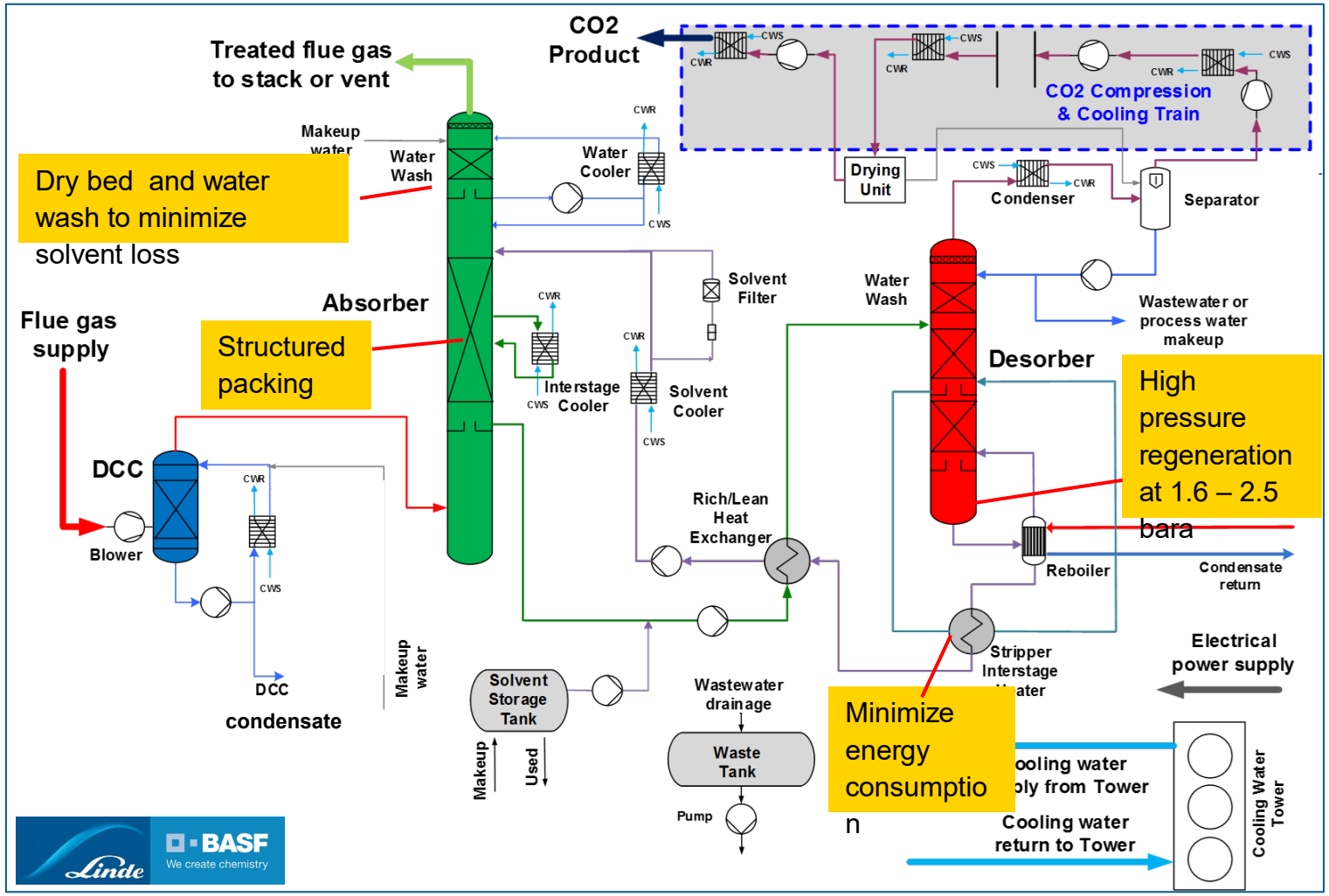
Project Overview

- Project cost $1.969 MM: DOE funding $1.5 MM; Linde cost share $0.469 MM
- Project duration: 24 months (October 2020 to September 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 Background
Process Design

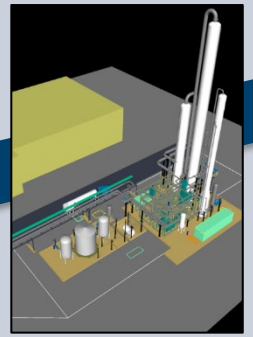


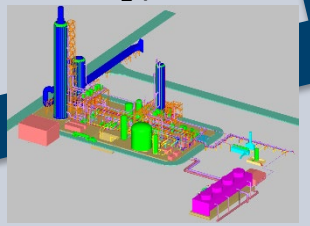
- Key advantages
  - 95% CO_2 capture rate
  - Reboiler duty ~2.7 GJ/tonne
  - High regeneration pressure
  - Minimal solvent loss to atmosphere
  - Minimal amine waste with the use of reclaimer
  - Structured packing in absorber
- Key challenges
  - Integration with existing flue gas stack
  - Shipping limitations for large single train plant
  - High CAPEX

Technology Background

Development and Scale-Up for Commercialization

Plant size and purpose	0.015 MWe Solvent selection	0.45 MWe pilot Solvent validation	1.5 MWe pilot Unique process/equip.	10 – 12 MWe Pre-commercial Validation	1st Commercial H_2 plant
Location Years	Ludwigshafen, Germany 2004	Niederaussem, Germany 2009 – 2016	NCCC Wilsonville, USA 2011 – 2017	Springfield, USA 2021 – 2026	US Gulf Coast ??
CO_2 Capacity, tpd	0.3	9 (30X)	30 (3X)	240 (8X)	2200 – 3700 (9 – 15X)
FG vol., MMscfd	0.07	2 (30X)	6.5 (3X)	52 (8X)	235 – 410 (5 – 8X)





Solid Foundation for Commercialization

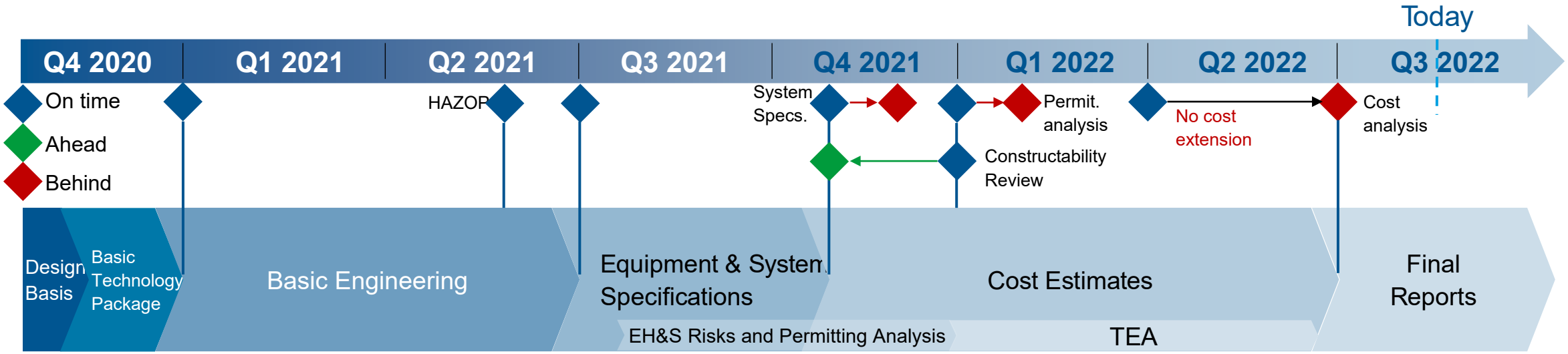
Technology Background
Host Site Selection

- 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

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)

Technical Approach/Project Scope

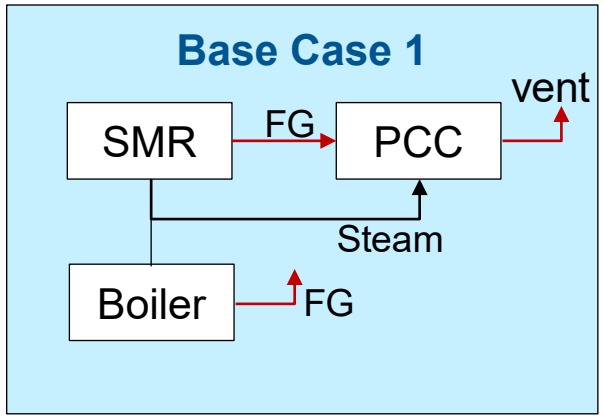


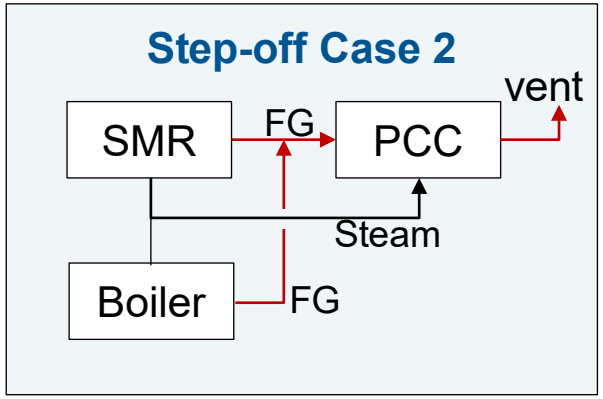
Decision Point	Date	Success Criteria
End of Project goal	09/30/2022	Cost estimate for PCC completed with accuracy of +/- 25%

+/-20% achieved

Design Basis

- Project type – Retrofit
  - No changes to SMR process
- Plant concept
  - CO_2 captured from SMR FG (base case 1)
  - Single train design
  - SMR export steam used in PCC unit
- CO_2 capture capacity ~1.4 million tonnes/year
- Case 1 used as the basis for engineering study
  - Scope 1 mitigation 88%
- Case 2 assessed during TEA
  - Scope 1 mitigation ~94%

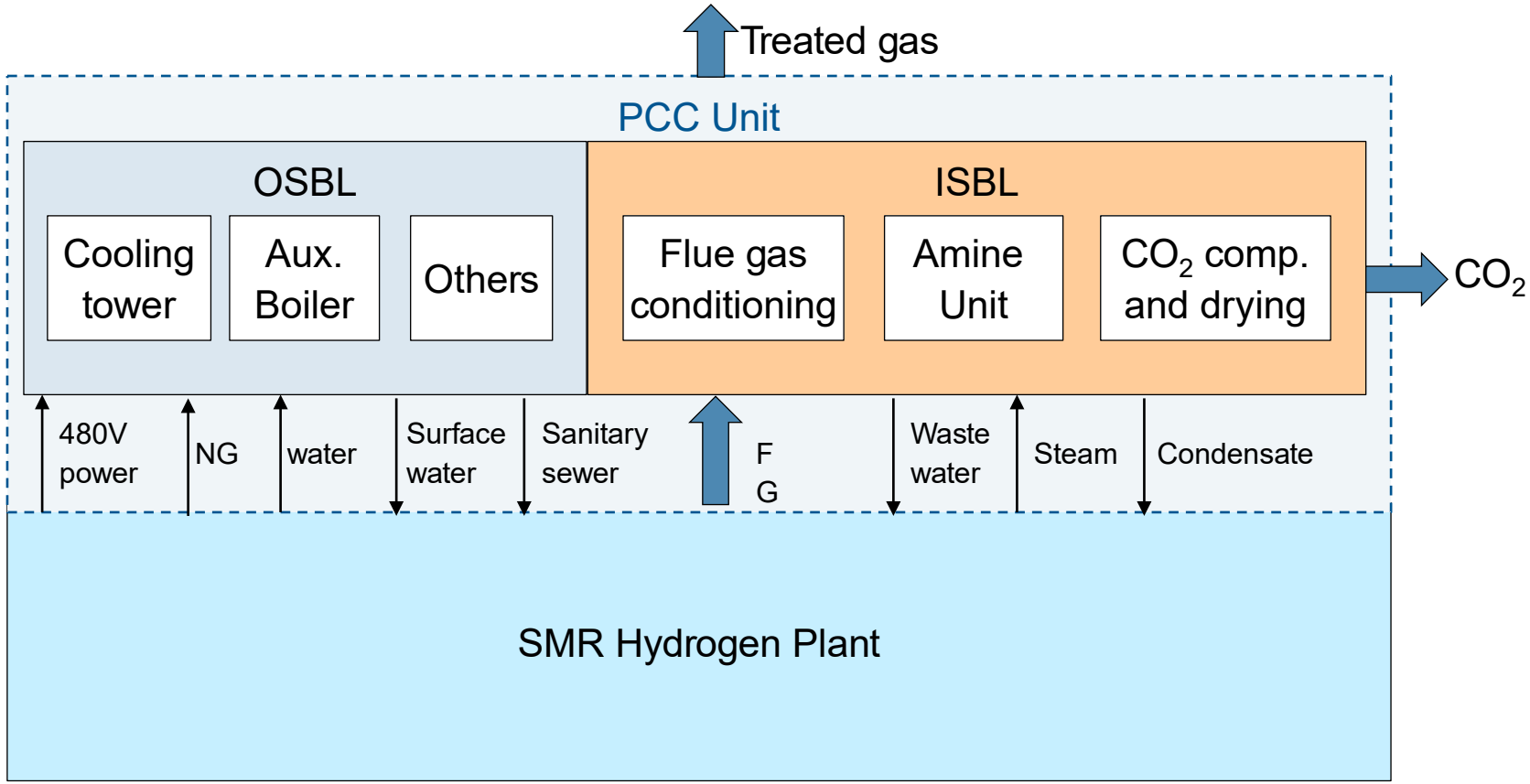




Feed - SMR Flue Gas	
Temperature, F	~320
Pressure, psia	14.7
Composition (mol%)	
N_2 + Ar + O_2	~62%
CO_2	~18%
H_2O	~20%
Trace impurities	< 100 ppm

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

System Boundary



CAPEX Estimate Approach

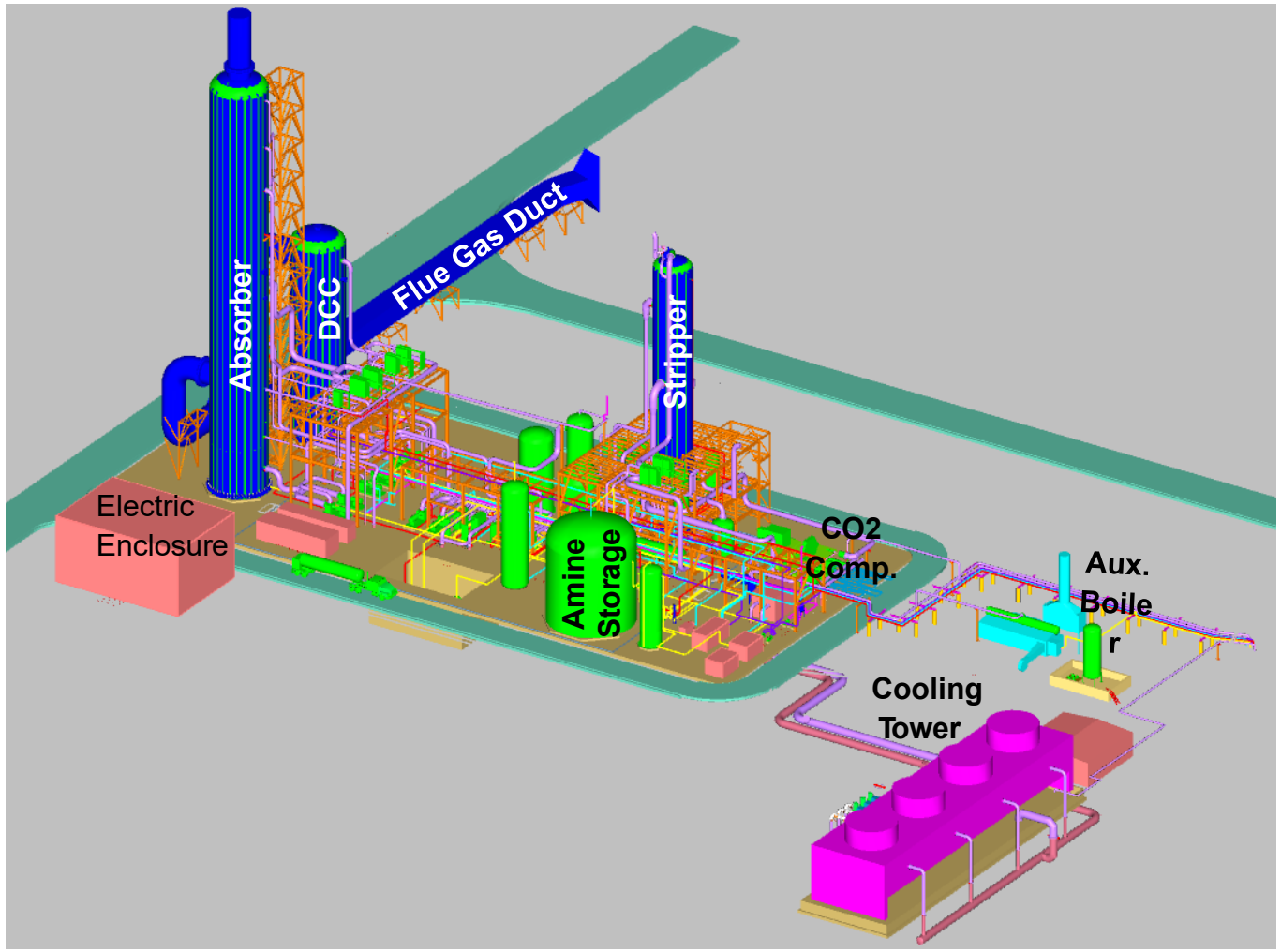
- Basis of design and basic technology package
- BFD and P&ID
- HAZOP of ISBL and OSBL scope
- Basic 3D Model
- Equipment specifications
- Equipment quotes and bid evaluations
- Logistics Study
- Constructability/layout reviews
- Permitting Analysis
- Execution schedule
- Risk analysis
- Owner’s costs
- TOC (total overnight capital) estimate
- TASC (total as-spent capital) estimate per DOE method

3D Model

PCC plant capacity – 3730 TPD

– Plot area ~13,000 m^2

– CO_2 99.9% at 2200 psig



Performance Summary

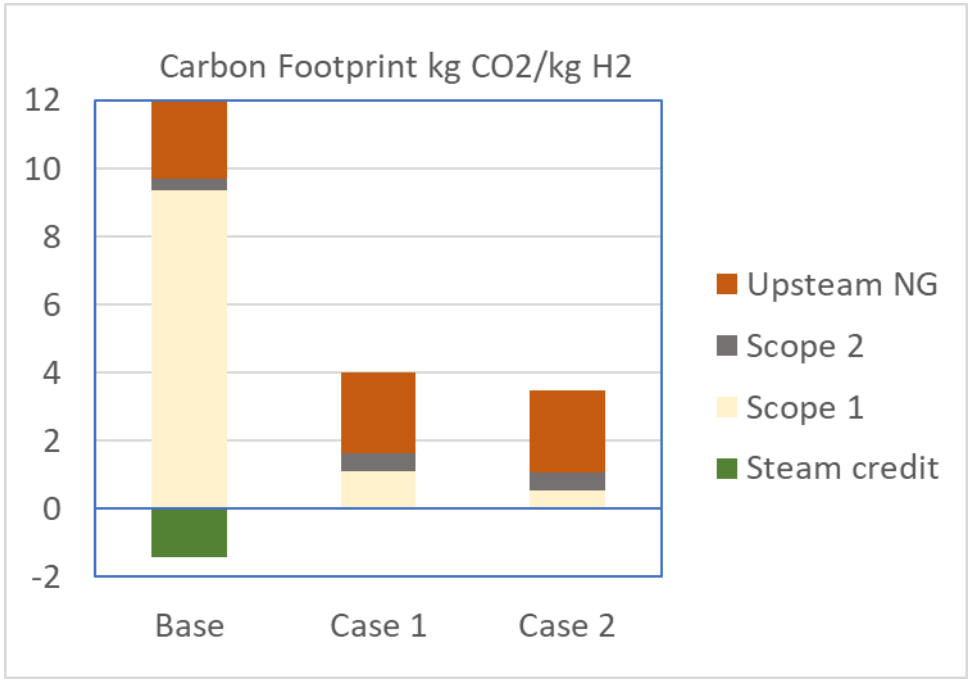
Process Performance

Variable	Consumption/T CO2
Reboiler duty	2.7 GJ*
Power	135 kWh**
Water	400 – 460 gal
Cooling tower blowdown	60 – 120 gal
Wastewater (Amine unit)	1 gal

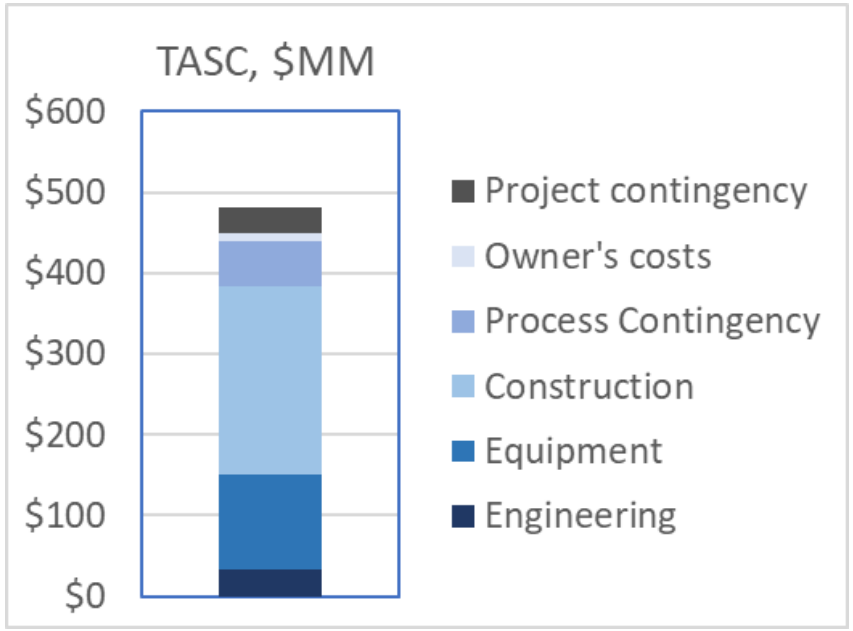
* Partly provided by SMR steam

**Partly supplied by steam turbine

Carbon Footprint



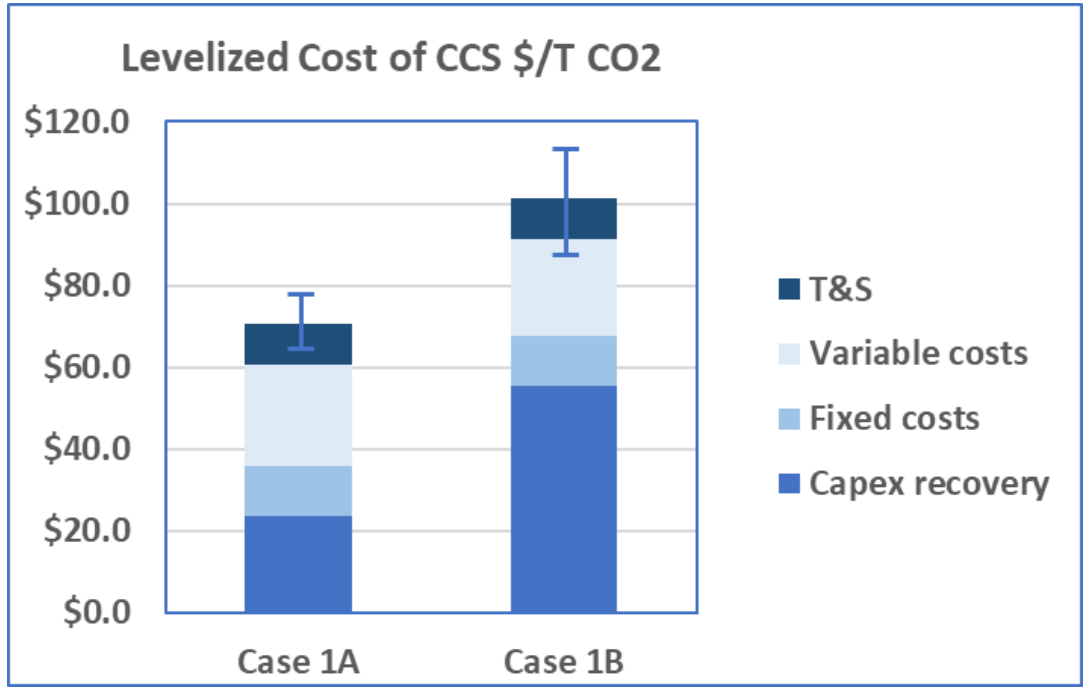
CAPEX Estimate



Total as spent cost (TASC)

- Equipment costs generally in line with the expectations
- Construction accounted for significant portion of total
  - Higher degree of on-site construction
  - Site-specific shipping limitations required more field assembly
  - Large equipment required more foundation/piling
- Higher risk profile for construction at this large scale
- CAPEX reduction opportunities have been identified

Technoeconomic Analysis Results



- NETL methodology adapted for levelized cost of CO_2 capture
  - CAPEX and OPEX of PCC plant converted to \$/T CO_2
  - Real dollars used as basis for the analysis
- Two scenarios of project financing considered
- LCOCCS ranges from \$71 to \$101/T CO_2
  - Financing assumptions can have large impact on costs
- CAPEX minimization important for high financing cost scenario

	Case 1A[1]	Case 1B[2]
Project life	30[1]	15
Debt	38%[1]	0%
Equity	62%[1]	100%
Real \$ cost of debt	5.15%[1]	2.94%[2]
Real \$ cost of equity	3.10%[1]	7.84%[2]
Fixed charge rate (FCR)	0.06	0.13

1. Financial parameters from 'Comparison of … H2 Production Technologies' DOE/NETL-2022/3041
2. Financial parameters from 'QGESS Cost Estimation Methodology ..' NETL-PUB-22580

Summary

- Completed engineering design for retrofitting existing SMR H_2 plant with PCC
- Capture capacity of ~1.4 MM tonnes/yr
- ~95% Capture rate achievable
- CCS cost could vary significantly depending on the financial assumptions
- Evaluation of CAPEX reduction options will be focus of future efforts

Thank you for your attention.

Linde Inc.
Minish M. Shah
Tel +1 716-879-2623
minish.shah@linde.com
www.linde.com