Final Project Report

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Engineering Study of Svante's Solid Sorbent Post-Combustion CO_2 Capture Technology at a Linde Steam Methane Reforming H_2 Plant

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Executive Summary

An initial engineering design study was performed for an advanced post combustion CO_2 capture (PCC) technology to be installed at a commercial-scale steam methane reforming (SMR) hydrogen plant located in the US Gulf Coast. The PCC process integrated the VeloxoTherm™ structured adsorbent technology from Svante for the CO_2 separation and CO_2 compression and purification and balance of plant systems provided by Linde. This pre-FEED equivalent study included following: (1) design basis, (2) basic engineering, including development of process flow diagrams and heat & material balances, (3) inside the battery limit (ISBL) equipment and systems specification, (4) balance of plant outside the battery limit (OSBL) equipment and systems specifications, (5) technology maturation plan, (6) hazard identification (HAZID) review, (7) environmental, health and safety (EH&S) assessment and environmental permitting analysis, (8) constructability review, (9) ISBL and OSBL EPC cost estimation, and (10) commercial-scale techno-economic analysis including capital expenditures (CAPEX) and operating expenditures (OPEX) and CO_2 capture cost estimates.

Majority of the engineering design efforts were focused on one specific process configuration referred to as the base CCS case. During the performance of the engineering design, several improvement opportunities were identified. Project team decided to evaluate two step-off cases. The design efforts for these cases were limited in scope and just sufficient to develop cost benefits compared to the base CCS case.

Following are key takeaways:

- The CO_2 capture unit is designed for 90% reduction in Scope 1 CO_2 emissions.
- The capacity of CO_2 capture unit for combined flue gases from the SMR H_2 plant and PCC auxiliary boiler is 1.435 MM tpy.
- The base CCS case used CO_2 distillation to achieve 99.9% purity and <10 ppm O_2.
- Single train design is technically feasible for the largest SMR hydrogen plant.
- Based on the preliminary permitting analysis at the host SMR site, permit amendment will be required due to new emissions from the PCC auxiliary boilers.

- The total CAPEX (or total overnight cost (TOC)) for the base CCS case is estimated to be $656 MM.
- The total cost of CCS (CO_2 capture and storage) is estimated to be $146/t.
- Two step-off cases were evaluated. The Catox case used catalytic oxidation for CO_2 purification to achieve 95% purity and <10 ppm O_2. The Energy Optimization case incorporated new heat integration concept into Catox case to reduce NG consumption.
- Total CAPEX for the Catox and the Energy Optimization cases are estimated to be $546 MM and $512 MM, respectively.
- The CCS costs for the Catox and the Energy Optimization cases are estimated to be $127/t and $124/t, respectively.

This report includes engineering study objectives, technology status, design basis, process design and control, EH&S assessment and permitting analysis, equipment list, constructability review, CAPEX, OPEX and CO_2 capture cost estimates and technology maturation plan.

1. Engineering Study Objectives

The objective of this study is to complete a preliminary engineering design of a commercial scale CO_2 capture plant retrofitted to a steam methane reformer (SMR), using the Svante VeloxoTherm™ solid adsorbent CO_2 capture technology. The overall system is designed to capture approximately 1,436,000 tonne/year CO_2 (at normal operating conditions) from combined flue gases of SMR and PCC auxiliary boiler. The CO_2 capture rate of ~92% was set in order to achieve 90% reduction in CO_2 emissions relative to baseline CO_2 emissions from the SMR. The engineering design covers inside the battery limits (ISBL) plant components including the CO_2 separation equipment from Svante and the CO_2 compression and purification equipment from Linde as well as outside the battery limits (OSBL) plant equipment such as cooling tower, electrical equipment and other balance of plant equipment.

The engineering design study shall include the following work: (1) basic design, including specific project scope definition and design basis, (2) basic engineering, including development of process flow diagrams and heat & material balances, (3) inside the battery limit (ISBL) detailed engineering, (4) balance of plant outside the battery limit (OSBL) detailed engineering, (5) technology maturation plan, (6) Hazard Identification (HAZID) review, (7) environmental, health and safety (EH&S) assessment and environmental permitting analysis, (8) ISBL and OSBL EPC cost estimation, (9) constructability review, (10) assessment of environmental permitting requirements, (11) commercial-scale techno-economic analysis including capital expenditures (CAPEX) and operating expenditures (OPEX) and (12) investigation of options for CO_2 Utilization.

2. Technology Status

Over the past 15 years, Svante has developed and began to commercialize an impactful technology to address greenhouse gas (GHG) emissions from industries including cement, lime, steel, oil & gas, pulp & paper, chemicals, aluminum, and hydrogen. It's technology ecosystem includes high-performance solid sorbents, including porous amines for direct air capture/carbon removal and novel metal-organic frameworks (MOFs) for post combustion point-source carbon capture, nanoengineered filters, and rotary contactor adsorbent machines, known as "RAMs". Solid sorbents, including MOFs, are a step change for the carbon capture industry. Their energy efficiency, resistance to degradation in the face of post-combustion flue gas impurities, and low cost of ownership make them ideal for carbon capture.

Svante's solid sorbents are laid onto thin sheets of film and stacked to create a filter or "structured adsorbent bed". These filters are inserted into the Svante RAM and capture CO_2 from diluted flue gas streams with high capacity and selectivity over water (Figure 1). The filters capture 90%+ of the total CO_2 emitted from industrial sources, using low-pressure steam for regeneration along with Svante's patented VeloxoTherm™, which utilizes temperature swing adsorption (TSA).

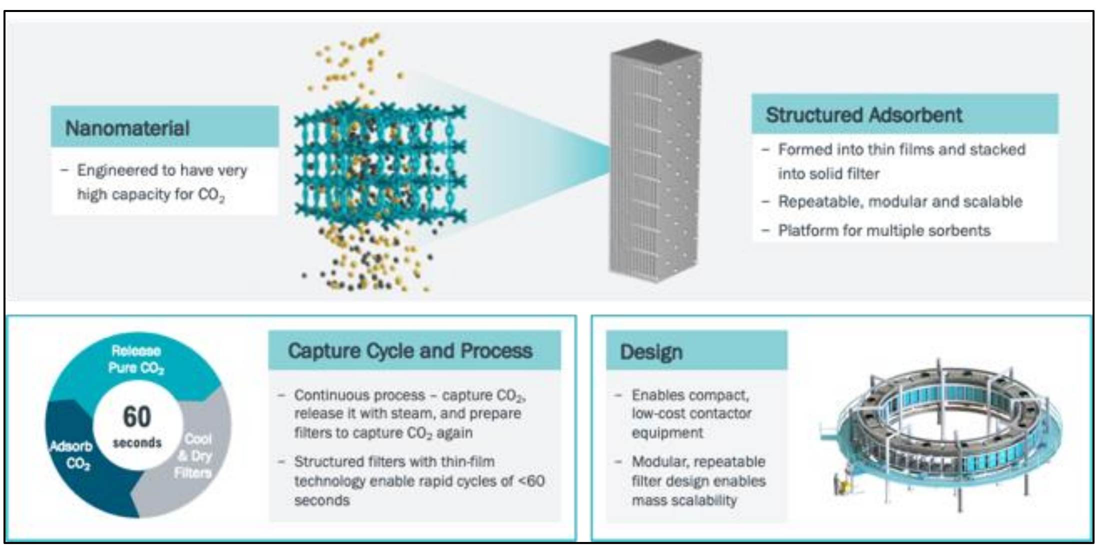

Figure 1. VeloxoTherm™ Rotary Adsorption Machine

Svante estimates that in order to meet the demands of the market, single RAM units will be required with CO_2 capture capacities of approximately 1,000 and 2,000 tonnes per day (TPD). To achieve this level of scale-up, Svante initiated a revised RAM design using a toroid bed arrangement. The advantage of this design is that the RAM will use standard sorbent modules derived from the current monolithic bed design used in the first two engineering scale units. This approach will simplify/standardize manufacturing and allow an accelerated path to unit scale-up. The modular design is also expected to yield cost benefit in both manufacturing and construction phases of our projects.

Svante anticipates that our lead machine to be deployed will be the "Ursa 1000" series RAM at 14m diameter and nominally rated at 500 TPD capture capacity (Figure 2). Larger capacity RAM machines nominally rated at 2000 TPD capture capacity and up to 24m in diameter, are expected to be the next series of machines to be deployed.

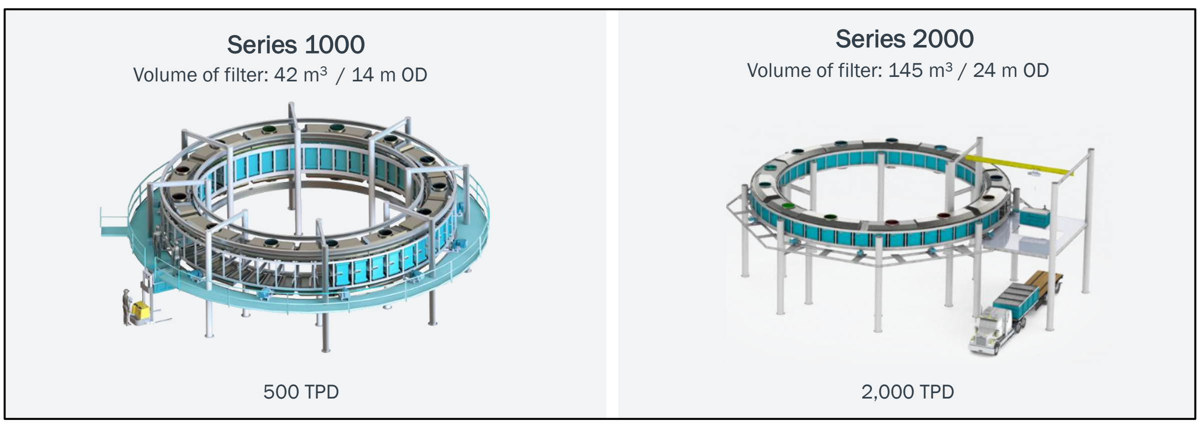

Figure 2. URSA 1000/2000

A single 400 Series filter bed (as currently produced for the DOE project – DE-FE0031944 project) is similar in size to the individual modules which makeup the repeatable design of the commercial-scale 1000 Series and 2000 series filter bed designs. The design configuration and scale of the 1000 Series reduces unit fabrication costs. Svante's filter bed design is a platform technology intended to work with a wide range of sorbents, making it highly adaptable to future sorbent development and optimization with both physisorbents and chemisorbents.

A full-scale prototype series 1000 RAM is currently being constructed in collaboration with Kiewit. The unit is completed and currently under testing and will be used to validate the sealing system, cost, and rotary drive system in preparation for commercial orders in 2024. Images of the prototype assembly and from the fabrication phase are provided in *Figure 3* and *Figure 4*.

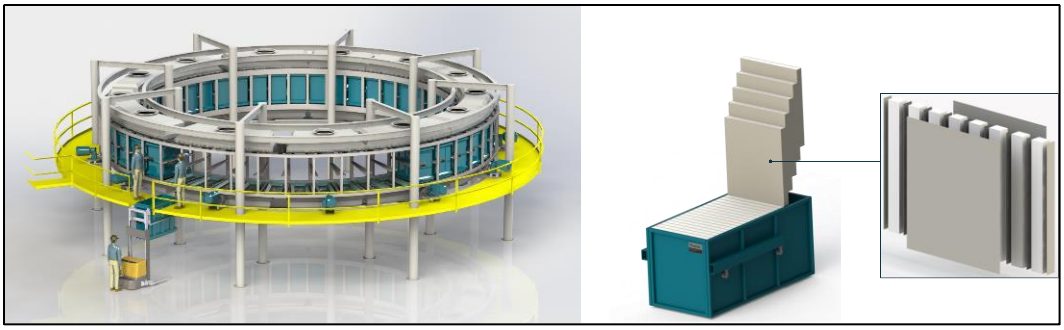

Figure 3. Design of 14m diameter RAM prototype

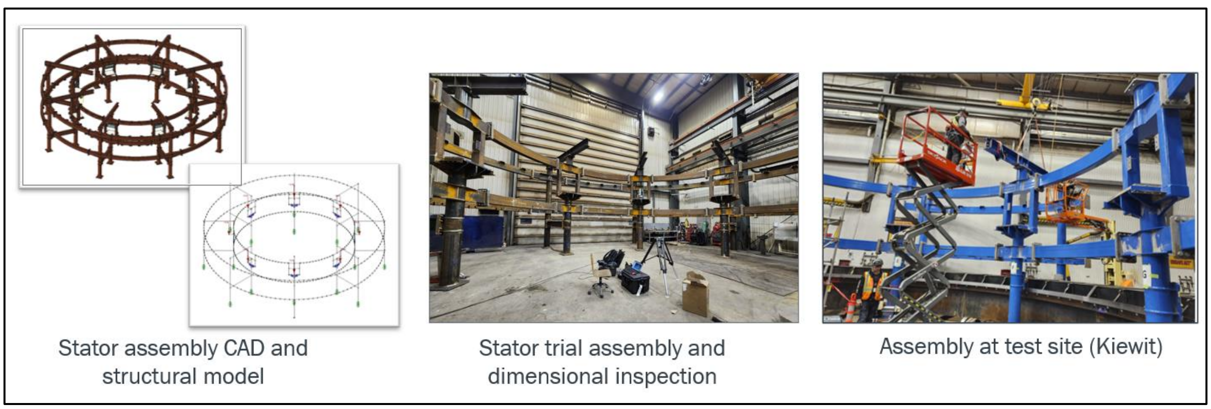

Figure 4. RAM Stator Assembly and Fabrication Status

Sub-systems such as seals and drivetrain require a mix of off-the-shelf and custom designed components. For these items, Svante will utilize a mix of preferred suppliers and specialist manufacturers (where dedicated tooling is required, such as casting, stampings, etc.). Svante expects to aggressively iterate the design to optimize it for manufacturing, maintainability, and transportability over the period leading up to the first commercial implementation. The RAM has been designed to allow for any typical good quality steel fabrication company to produce the various elements. This approach allows for RAM to be built by manufacturers globally or regionally in the US and Canada, enabling Svante to achieve speed to market and also limit logistical challenges associated with a single point of manufacture.

2.1 Advanced Sorbent Development

Background

The solid adsorbent used is contained in a RAM which is the concept at the core of the VeloxoTherm™ technology. The key to this application is a new class of advanced sorbent materials, based on MOFs. The MOF sorbent powder is coated onto a carbon-based substrate. These materials exhibit sharper temperature and pressure swing absorption and desorption which allow for lower energy loads and faster kinetic rates for process intensification. The proprietary MOF used in this study, CALF-20, also exhibits unique resistance to oxygen, SOx NOx, impurities and moisture swing.

For this application, the VeloxoTherm™ process uses a rotating adsorbent bed 5-step cycle to execute the adsorption, regeneration, and conditioning functions as shown in Figure 1. The adsorbent material is secured within a rotating cylindrical frame, known as a RAM. The frame of the RAM is divided into distinct zones to allow for the steps of adsorption, regeneration, and conditioning.

Sorbent Selection

A key challenge for industrial applications (cement, hydrogen, SMRs, and refineries) is the endurance of sorbent materials during exposure to water, SOx, NOx, and oxygen. Water plays an important role in the Svante VeloxoTherm™ carbon capture process, steam is used for filter regeneration and moisture condensation is present in the flue gas. During the flue gas feed step, the sorption of water interferes with CO_2 adsorption. For most physisorbents such as MOFs, water blocks active CO_2 sorption sites (competitive adsorption and capillary pore condensation). Pore condensation is not favorable as it consumes a major portion of regeneration energy. It also drastically increases operating costs of capture due to the re-evaporation of condensed water, which requires enthalpy from steam.

CALF-20 represents a physical adsorbent that is water tolerant during the feed step and does not exhibit degradation in the presence of NOx and SOx, making it the optimal solution when compared to chemical sorbents. The CALF-20 adsorbent performance improves at increasing CO_2 concentrations making it suitable for the SMR application.

CALF-20 has been lab tested under DOE Cooperative Agreement No. DE-FE0031732 and has been in field testing since January 2021 at a cement plant in Canada. CALF-20 is also being tested at Chevron's oil field on a pilot scale under DOE Cooperative Agreement DE-FE0031944.

Sorbent Testing

In addition to small-scale testing of amine and MOF based sorbents, Svante has performed larger scale testing on multi bed Process Demonstration Units [0.1 TPD] and engineering scale pilot plants. A current summary of test hours/facility is provided in Figure 5.

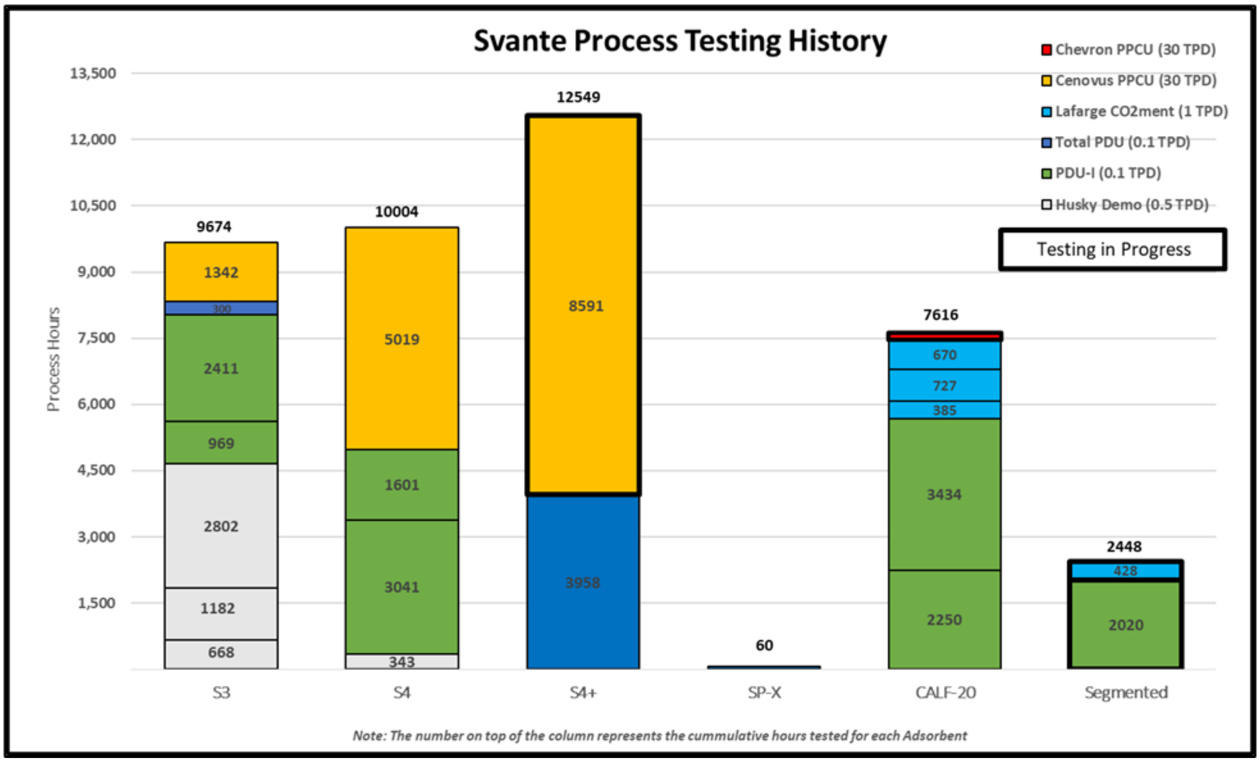

Figure 5. Svante's Accumulated Hours of Test/Operation for each Adsorbent

In total Svante has accumulated more than 42,000 hours of testing on multiple generations of amine and MOF sorbents. Most of the experimental and plant data required for the design of the First of a Kind (FOAK) commercial plant will come from the Second of a Kind (SOAK) 400 Series Technology Package from the Chevron demonstration project.

3. Design Basis

Information presented in this section is relevant for the base case process configuration. While most of the information is applicable to two step-off cases, any changes in process configurations and CO_2 capture rates are described later. The overall system has been designed to achieve 90% reduction in direct CO_2 emissions compared to baseline SMR operation. Since PCC auxiliary boiler is required to generate steam for CO_2 separation from flue gas, the capture system is designed to capture ~92% CO_2 from both SMR and aux. boiler flue gases (Figure 6) in order to achieve 90% reduction vs. the baseline. The CO_2 capture capacity is ~1.436 MM tonnes/year of CO_2 for normal operation of SMR (100% of design capacity). The location of this plant is the existing Linde H_2 facility in the US Gulf Coast.

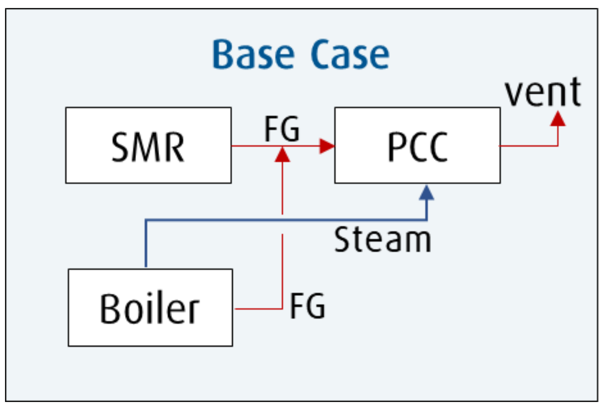

Figure 6. Simplified Schematics of the Base Case

As shown in Figure 7 below, the plant was divided into two separate process areas with a different party responsible for the design of each area: Svante-Kiewit team for Capture Plant and PCC Auxiliary Boiler and Linde for CO_2 Compression and Purification and Balance of Plant (BOP). The plant is a single train design with two URSA 2000 RAMs in parallel.

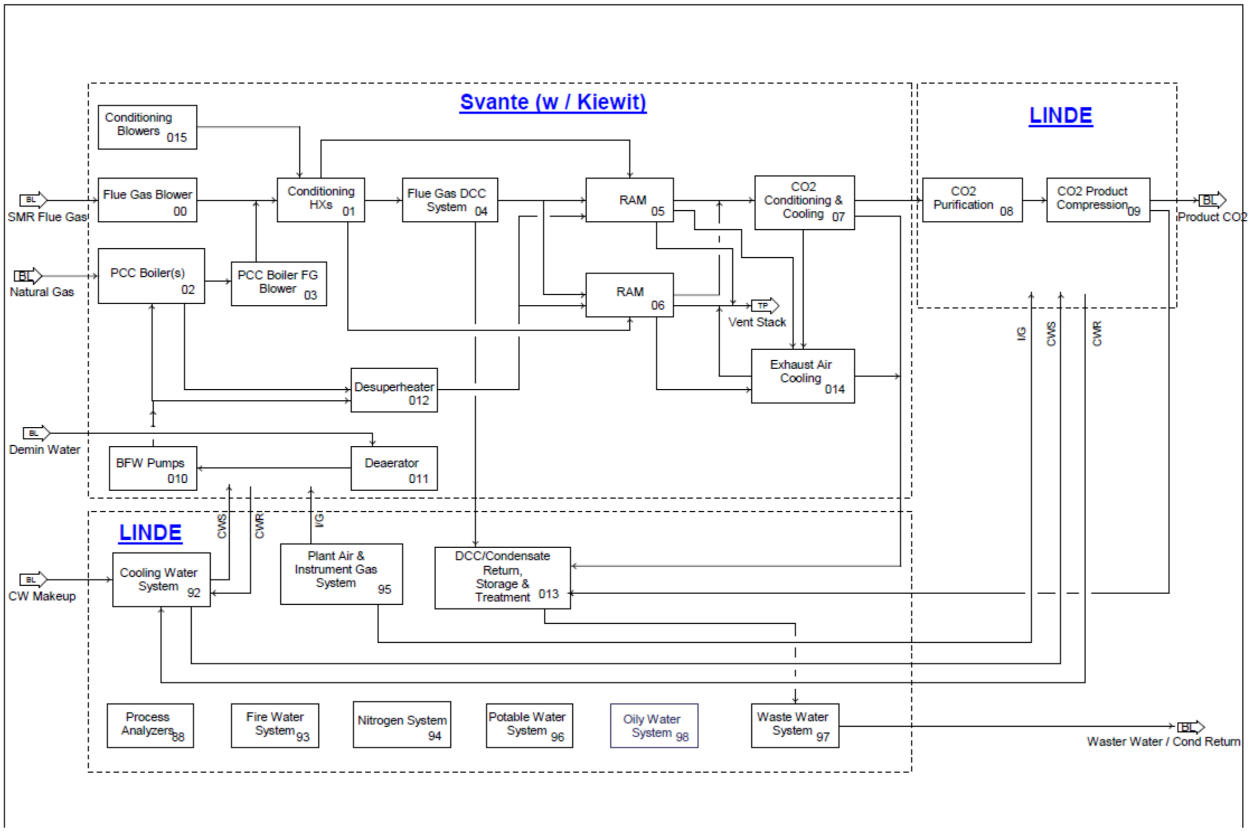

Figure 7. Block Flow Diagram of Base Case used in the Engineering Design

Svante/Kiewit/KSI:

- Svante Capture Plant.
- PCC Aux. Boilers

Linde:

- CO_2 purification and compression.
- Cooling water system
- Plant drainage system
- Electrical power integration
- Utilities
- Flue Gas Condensate collection and treatment

3.1 General

Definitions and Abbreviations

Abbreviation	Explanation
BD:	Blowdown
BEC:	Bare Erected Cost
BFD:	Block Flow Diagram
BFW:	Boiler Feed Water
BOP:	Balance of Plant
CAPEX:	Capital Expenditure
CW:	Cooling Water
DCC:	Direct Contact Cooler
FG:	Flue Gas
FOAK:	First of a Kind
ISBL:	Inside Battery Limit
MOF:	Metal Organic Framework
OPEX:	Operating Expenditure
OSBL:	Outside Battery Limit
PEC:	Purchased Equipment Costs
PSA:	Pressure Swing Adsorption
RAM:	Rotary Adsorption Machine
SMR:	Steam Methane Reforming
SOAK:	Second of a Kind
TBD:	To Be Determined
TEA:	Techno-Economic Assessment
TPC:	Total Plant Cost
TPD:	Metric Tonne per Day
TPH:	Metric Tonne per Hour
TOC:	Total Overnight Cost
TSA:	Thermal Swing Adsorption
VSD:	Variable Speed Drive

3.2 Site Conditions

General Site Information

The location of this plant is the existing Linde H_2 facility in the US Gulf Coast. The plant is adjacent to an existing refinery designed to process crude oil and produce conventional petroleum products. Linde's H_2 SMR plant has been in operation for more than nine years. It is integrated with Linde's extensive Gulf Coast H_2 pipeline system.

Atmospheric Conditions

- Elevation: 3m
- Atmospheric Pressure: 101.27 kPa
- Summer Design DB Temperature: 43 °C

- Summer Design WB Temperature: 33°C
- Winter Design DB Temperature: -4°C

Severe Atmospheric Conditions

- Gulf Coast Corrosive atmosphere

Wind Design

- Code: ACSE-7-10
- Exposure Category: C
- Importance Factor: 1
- Wind Velocity: 148 mph
- Occupancy Category: II
- Topographic Factor (K_{ZT}): 1.0
- Directionality Factor (K_D): 0.85, 0.90, 0.95

Snow Load

- Ground Snow Load: 0 psf

Rainfall

- Annual Average: 60.5 inch
- Frequency: 100 year
- Maximum in one hour: 4.93 inch

Seismic Zone

- Applicable Codes: IBC 2015
- Occupancy Category: II
- Importance Factor: 1.25
- Site Class: D
- Spectral Response Acceleration, Short Period Ss: 0.132
- Spectral Response Acceleration, 1st Period S1: 0.064
- Seismic Design Category: B

3.3 Feedstock

The flue gas conditions entering the capture plant can be seen in Table 1 and

Table 2. Two separate feed streams exist, the flue gas coming from the SMR and the flue gas from the PCC Aux Boilers which are providing steam to the capture plant. Both streams have independent blowers to control the flowrate and are combined before entering the capture plant. The

capture plant equipment sizing was done using 10% higher flowrate than the values shown below to account for periods of high production in the SMR as well as to provide design margins for normal operation.

Table 1. SMR Flue Gas Conditions

Component	Unit	
Temperature	°C	148.9
Pressure	bar(a)	1.013
Mass Flowrate	kg/hr	595,400
Volume Flowrate	MMscfd	412.4
CO_2	mol %	16.22
H_2O	mol %	17.85
$N_2 + O_2 + Ar$	mol %	65.93
NOx	ppm	6 ppm average 12 max
SO_2	ppm	0.2 pppm average 6 max

Table 2. PCC Aux Boiler Flue Gas

Component	Unit	
Temperature	°C	158.3
Pressure	bar(a)	1.013
Mass Flowrate	kg/hr	240,803
Volume Flowrate	MMscfd	174.1
CO2	mol %	8.12
H2O	mol %	16.71
N2 + O2 + Ar	mol %	75.17
NOx	ppm	9
SOx	ppm	0

3.4 Design Capacity

The plant has been designed to achieve a 90% reduction vs. baseline CO_2 emissions from SMR flue gas. The plant at normal operating conditions will capture approximately 3935 TPD CO_2 from combined flue gases from SMR and the PCC Aux Boiler with an overall plant CO2 capture efficiency of

92%. For this capacity, two Svante Ursa 2000 RAMs are required in parallel. The plant equipment is sized for 10% higher flow than the normal operating rate to allow for design margin.

3.5 Products

The CO_2 product specification leaving the plant can be seen in Table 3.

Table 3. Carbon Dioxide (CO_2) Product Specification

Parameter	Unit	Specification
Flow (normal operation)	MT/d	3933
Temperature	°C	<48.9
Pressure	bar(a)	152.6
Composition	**Unit**	**Specification**
CO_2	mol%	>95
Water	lbs/MMscf	<30
Nitrogen, Ar, non-condensable	mol%	<4
Oxygen	ppmw	<10

Equipment Sizing Criteria

The equipment sizing criteria for the Svante Capture Plant is outlined in Table 4. As mentioned earlier, the CO_2 volumes in this Table are corresponding to 110% of normal operations capacity of SMR. The recovery within the Svante unit is 92.3% to ensure a 90% reduction vs. baseline SMR flue gas CO_2 emissions.

Table 4. Svante Capture Unit Design Criteria

Performance	Unit	Value
SMR Flue Gas CO_2 Concentration	%v/v dry	19.74
CO_2 from SMR	TPD Metric	3879
CO_2 from Auxiliary Boiler	TPD Metric	819
CO_2 Capture Recovery	%	92.3
Product CO_2 Purity	%v/v dry	95
Steam: Product CO_2 Ratio	kg/kg CO2	1.22
CO_2 Production Capacity	TPD Metric	4336
CO_2 Product Pressure	kPag	0
Adsorbent Selection		CALF20

3.6 Utilities

Demineralized Water

Demineralized water required for water make-up to the PCC Aux Boiler steam system will be suppled from the host site to the battery limit of the plant. The expected composition and conditions of the demineralized water can be seen in Table 5.

Table 5. Demineralized Water Conditions

Component	Unit	
Temperature	°C	10
Pressure	kPag	34.5
O_2	ppb	<100
Iron (Fe)	ppb	<100
Total Alkalinity ($CACO_3$)	ppm	<1000
Silica	ppb	<150
Conductivity	uS/cm	<7000

Boiler Feed Water

Boiler feed water (BFW) for the PCC Auxiliary Boilers will be supplied from a new deaerator. The BFW conditions to the boiler can be seen in Table 6.

Table 6. Boiler Feedwater

Parameter	Unit	
Temperature	°C	108
Pressure	kPag	1673

Steam Generation

The steam required in the capture plant for regeneration of the adsorbent will be supplied from three low pressure natural gas fired boilers. The steam conditions leaving the boilers can be seen in Table 7. The flue gas generated from the boilers will be combined with flue gas from the SMR and captured. The flue gas conditions can be seen in

Table 2. The steam condensate will be recovered and recycled to the deaerator for boiler feed water.

Table 7. Steam Conditions

Parameter	Unit	
Temperature	°C	170
Pressure	kPag	689.5
Steam Quality	%	99.5

Potable Water

Potable water will be supplied by the host refinery for sinks, safety showers, etc.

Fire Water / supplied by customer

Firefighting water to the capture plant will be provided by tying into and extending the existing fire water loop at the facility. Additional hydrants and other firefighting equipment is planned to be added as required on the expanded system.

Nitrogen

Nitrogen will be used for purging, startup, and instrument gas backup. The nitrogen will be supplied from the host site's high pressure nitrogen pipeline and let down via let down station. The nitrogen is dry, oil free, and contains less than 10 ppmw O_2.

Instrument Gas

An instrument air compression, drying, and receiver system will be installed as part of the balance of plant scope. The instrument air is backed up by nitrogen for reliability and peak demand periods (e.g. startup, shutdown, etc.).

Cooling Water

The cooling water required in the plant will be supplied from a new cooling tower. A new cooling tower, cooling water pumps, cooling water blowdown tank, cooling water blowdown pumps, side stream filter, and chemical treatment system will be installed to meet the cooling water needs for the PCC plant.

The design basis for the new cooling tower can be seen below in Table 8 . The design criteria is based on the design/data from the existing cooling water system on site currently supplying the SMR.

Table 8. Cooling Water Design Assumptions

Cooling Water Design Assumptions	
Dry Bulb Temperature, F (1% day)	92
Mean Coincident Wet Bulb Temp, F	79
Relative Humidity, %RH	70
Number of Cycles	7.5
Cooling Water Supply Temp, Max F	92
Design Cooling Water Temp Rise, F	15
Cooling Water Supply Pressure at CW Pump Discharge, psig	67
Allowable Pressure Drop, psi	Normal 10
	Max 15
Typical Cooling Water Composition:	
pH	8.5
Specific Conductance, mmhos	2520
M Alkalinity, ppmw as CaCO3	252
Sulfur, ppmv total as SO4	817
Chloride, ppmw as ion	312
Total Hardness, ppmw as CaCO3	576
Calcium Hardness, ppmw as CaCO3	396
Magnesium Hardness, ppmw as CaCO3	180
Silica, ppmw as SiO2	84

Natural Gas

Natural gas will be supplied at a higher pressure for PCC Aux boilers fuel gas at the battery limit. High pressure natural gas will be let down to a lower pressure and used for the PCC Aux boilers. The conditions and composition of the natural gas can be seen in Table 9.

Table 9. NG Conditions

Temperature, ^oF	60-100
Pressure, psig min	20.9
Composition, mole% (unless noted)	
CH_4	90.0
C_2H_6	5.0

N_2	5.0
Total Sulfur as H_2S, ppmv	5.0

Electricity

60 hz/13.8 kV, 3 phase.

Online Analyzers of Products

See below requirements for analysis of gas and liquid streams for control and monitoring of the plant (Table 10).

Table 10. Analyzer Requirements

Area	Location	Analyte
Svante Capture Plant	Boiler FG	CEMS
Svante Capture Plant	Boiler FG	CO_2
Svante Capture Plant	Boiler FG	O_2
Svante Capture Plant	RAM #1 Outlet	CO_2
Svante Capture Plant	RAM #1 Outlet	O_2
Svante Capture Plant	RAM #2 Outlet	CO_2
Svante Capture Plant	RAM #2 Outlet	O_2
Svante Capture Plant	RAM Reflux	CO_2
Svante Capture Plant	RAM Reflux	O_2
Svante Capture Plant	SMR Flue Gas	CO_2
Svante Capture Plant	SMR Flue Gas	O_2
Svante Capture Plant	Vent Stack	CEMS
Svante Capture Plant	Vent Stack	CO2
Svante Capture Plant	Vent Stack	O2
BoP	SMR Flue Duct	CEMS
BoP	Demin. Water	pH, Conductivity
BoP	Cooling Water Return	pH, Conductivity
BoP	N2 Supply Line	Moisture in N2
BoP	Cooling Tower BD	pH, Conductivity, Free Chlorine
BoP	Cooling Water Return	Polymer, Free Chlorine, delta PO4, Unfiltered PO4, Corrosion (CS), Corrosion (Copper),
BoP	Clarified Water	pH, Conductivity
BoP	SMR Flue Duct	CEMS

Noise Limits

Allowable noise level:

- At 1m from source: 95 dBA
- At property limits: N/A

3.7 Limits for Effluents and Emissions as per local Regulations

Wastewater

Utility wastewater sources, such as cooling tower blowdown, cooling tower side stream filter back wash, DCC condensate, deaerator drain, PCC boiler blowdown and quench water, cooling water sampling package drain, wastewater from CO2 purification and compressor will be directed to the diverter sump. The pH of the wastewater will be measured in the diverter box. If the pH of the wastewater is acceptable, then the wastewater will be transferred to the main wastewater sump. If the pH of the wastewater is not acceptable, then the wastewater will be transferred to the treatment wastewater sump, where additional treatment will be performed prior to pumping to the main wastewater sump. Wastewater entering this main wastewater sump will be discharged to the battery limits.

Emissions to Atmosphere

The boiler flue gas stack emission limits are as follows:

Environmental/authority limitations to be considered:	☐ No limitations required ☒ Yes, according below requirements	
	Maximum load	
NOx at 3 % O_2 in the dry flue gas max	ppmv	8
CO at 3 % O_2 in the dry flue gas.	ppmv	50
NH_3 (in case of SCR)	ppm	10
Opacity at 3 % O_2 in the dry flue gas	% max	5

4. Process Design

4.1 Block Flow Diagrams

Block Flow diagrams for the Svante CO_2 Separation Plant and Linde CO_2 Purification and Compression are shown in Figure 8 and Figure 9. The BOP equipment is shown earlier in Figure 7.

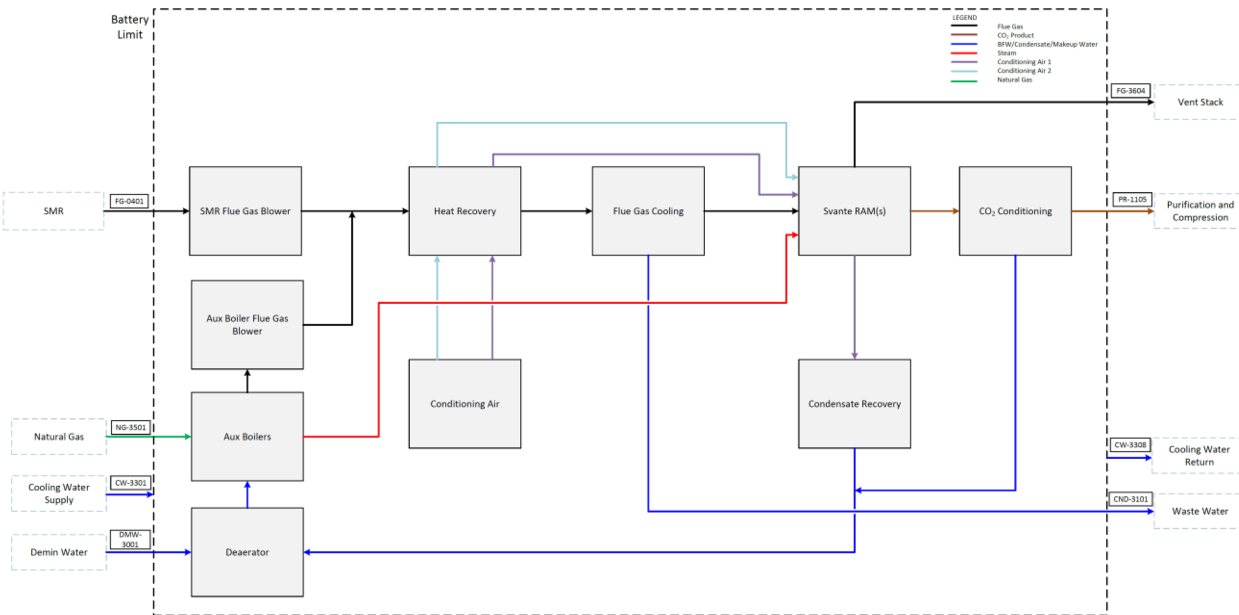

Figure 8. BFD – Base CCS Case – Svante Capture Plant and PCC Auxiliary Boilers

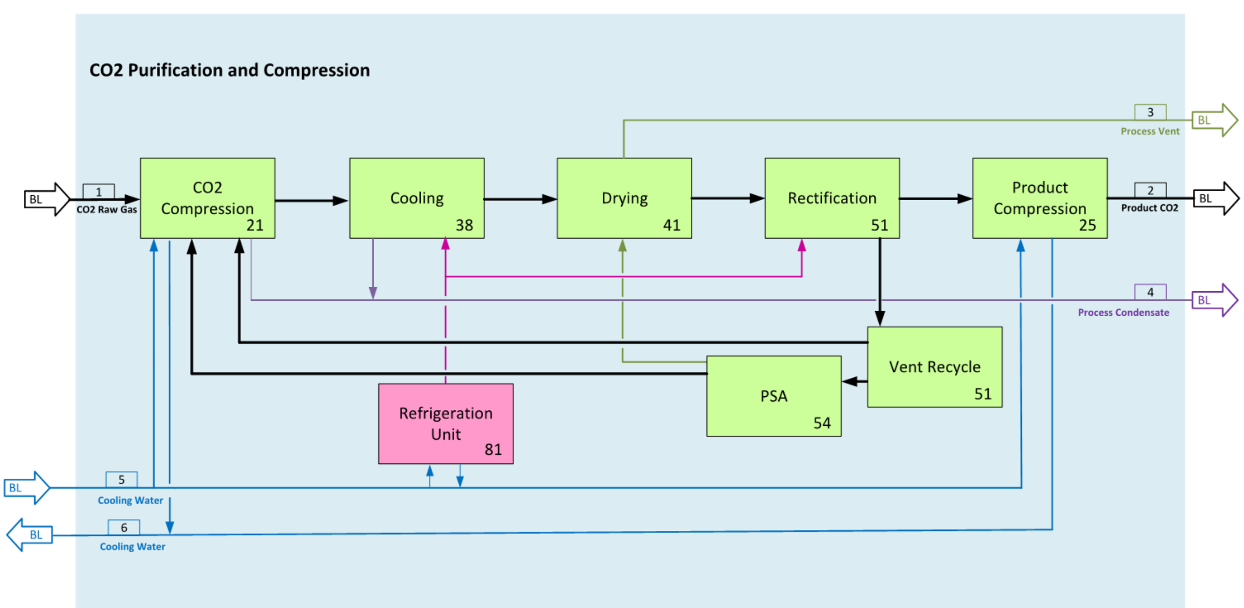

Figure 9. PFD – Base CCS Case – CO_2 Purification and Compression

4.2 Process Description

Svante CO_2 Separation Plant

The flue gas system combines flue gas from the SMR and flue gas from the Auxiliary Boilers. The SMR flue gas system ties in to the existing SMR at the exhaust stack. This combined stream is sent via heat recovery to a single Direct Contact Cooler (DCC) for final conditioning and cooling prior to flowing to the RAMs for adsorption. The Conditioning air streams required for cooling and conditioning the adsorbent are heated in the heat recovery unit.

The treated flue gas from the DCC enters the RAMs and the CO_2 is adsorbed onto the adsorbent beds. The remaining flue stack gas constitutes primarily N_2, O_2 and H_2O are exhausted to the stack after the CO_2 has been adsorbed.

Low pressure steam for the capture plant is generated by 3 package boilers. The BFW for the boilers is produced within the capture plant battery limit. Steam condensate is sent to the Deaerator as part of the boiler package to remove almost all dissolved oxygen prior to being sent to the boiler. Demineralized water from the refinery is supplied as make-up water to the Deaerator. The steam produced in the boilers is sent to the RAM for desorption of the CO_2 from the Svante adsorbent.

The product CO_2 stream leaving the RAM is cooled and the moisture is removed in the conditioning step before being sent to the purification and compression system.

CO_2 Purification and Compression

The raw CO_2 stream generated in the SVANTE Carbon Capture Plant is compressed by the Raw CO2 Compressor and condensed water is separated from the gas stream. The compressed raw CO_2 is dried, cooled to liquefaction temperature and then purified in a distillation column to achieve <10 ppm O2 in the CO_2 product. The purified CO_2 is warmed and then compressed in a product compressor. The vent gas from the column is warmed and processed in a PSA unit to recover additional CO_2 and minimize losses to atmosphere. Required refrigeration for the CO2 cooing and liquefaction is provided by the refrigeration unit using ammonia as refrigerant.

Balance of Plant

The balance of plant consists of a new cooling water system that includes a new cooling tower, cooling water pumps, cooling water blowdown tank, cooling water blowdown pumps, side stream filter, and chemical treatment system, plant air and instrument gas system, DCC condensate return, storage and treatment system, process analyzers, fire water system, nitrogen system, potable water system, oily water system, and wastewater system.

4.3 Heat and Mass Balances

The stream summary for the carbon capture plant for the normal operation case is provided in Table 11.

Table 11. Stream Summary for Base CCS Case

		FG-0401	NG-3501	CW-3301	DMW-3001	FG-3604	PR-1105	CW-3308	CND-3101
V-L Mole Fraction		1.00	1.00	0.00	0.00	1.00	1.00	0.00	0.00
CO2		0.1622	0.0000	0.0000	0.0000	0.0036	0.8762	0.0000	0.0000
H2O		0.1785	0.0000	1.0000	1.0000	0.0720	0.0777	1.0000	1.0000
N2		0.6411	0.0500	0.0000	0.0000	0.7705	0.0444	0.0000	0.0000
O2		0.0182	0.0000	0.0000	0.0000	0.1539	0.0017	0.0000	0.0000
CH4		0.0000	0.9000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C2H6		0.0000	0.0500	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C3H8		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total		1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate	kgmol/hr	20,604	702	795,189	4,209	84,119	4,260	795,189	3,368
V-L Flowrate	t/h	595.4	12.2	14,325.4	75.8	2,352.5	175.8	14,325.4	60.7
Fuel Flowrate	kg/hr	-	-	-	-	-	-	-	-
Temperature	°C	149	16	32	10	66	62	40	59
Pressure	kPa(g)	0.0	144.8	451.3	34.5	0.0	0.0	351.3	350.0
Density	kg/m^3	1	1.77	1,002	1,019	0.98	1.47	996	981
V-L Molecular Weight	kg/kgmol	28.9	17.3	18.0	18.0	28.0	41.3	18.0	18.0
Mass Enthalpy	kJ/kg	-3562	-4154	-15820	-15917	-627	-8784	-15783	-15700
V-L Flowrate	lbmol/hr	45,424	1,548	1,753,089	9,280	185,451	9,392	1,753,089	7,424
V-L Flowrate	lb/hr	1,312,549	26,846	31,582,073	167,185	5,186,317	387,517	31,582,073	133,747
Fuel Flowrate	lb/hr	-	-	-	-	-	-	-	-
Temperature	°F	300	60	89	50	152	143	104	138
Pressure	psi(g)	0.0	21.0	65.4	5.0	0.0	0.0	50.9	50.8
Density	lb/ft^3	0.05	0.11	62.58	63.58	0.06	0.09	62.18	61.27

		Raw CO2 from Svante Stream 1 / PR-1105	Product CO2 to BL Stream 2	Process Vent to Atm Stream 3	Condensate from CO2 Purification	Condensate to BL Stream 4	CW Blowdown	CWS Stream 5	CWR Stream 6	Aux Boiler BD Quench
V-L Mole Fraction		1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
CO2		0.8762	0.99991	0.04024	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O		0.0777	0.00000	0.02009	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
N2		0.0444	0.00008	0.90521	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
O2		0.0017	0.00001	0.03447	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CH4		0.0000	0.00000	0.00000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C2H6		0.0000	0.00000	0.00000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total		1.0000	1.00000	1.00000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
V-L Flowrate	kgmol/hr	4,260	3,724.2	209.2	326.5	14,311	9,473	1,022,743	1,022,743	757.9
V-L Flowrate	t/h	175.8	163.9	6.0	5.9	257.8	170.7	18,424.8	18,424.8	13,653.3
Fuel Flowrate	kg/hr	-	-	-	-	-	-	-	-	-
Temperature	°C	62	49	42	42	32.2	32.2	32.2	41.1	32.2
Pressure	kPa(g)	0.0	15,175.0	0.0	150.0	35.0	70.0	482.8	379.3	310.0
Density	kg/m^3	1.47	671.60	1.09	994.65	1,001.93	1,001.94	1,002.08	995.27	1,002.02
V-L Molecular Weight	kg/kgmol	41.26	44.01	28.59	18.03	18.02	18.02	18.02	18.02	18.02
Mass Enthalpy	kJ/kg	-8784	-9140	-706.8	-15,808.0	-15,856.6	-15,856.6	-15,856.2	-15,818.0	-15,856.4
V-L Flowrate	lbmol/hr	9,392	8,210	461	720	31,549	20,885	2,254,739	2,254,739	1,671
V-L Flowrate	lb/hr	387,517	361,325	13,190	12,976	568,361	376,250	40,619,358	40,619,358	30,100
Fuel Flowrate	lb/hr	-	-	-	-	-	-	-	-	-
Temperature	°F	143	120	108	108	90	90	90	106	90
Pressure	psi(g)	0.0	2200	0.0	21.5	5.0	10.0	70.0	55.0	45.0
Density	lb/ft^3	0.09	41.93	0.07	62.09	62.55	62.55	62.56	62.13	62.55

4.4 Utilities

The total utilities demand is summarized in Table 12

Table 12. Overall Utility Summary – Base CCS Case

Utility	Unit	Value
Natural Gas	MMBtu/hr (HHV)	600
Demin Water	US gpm	339
Clarified Water	US gpm	2,600
Electric Power Usage	kW	52,908
Cooling Water Circulation Rate	US gpm	80,950

The design case assumed condensate condensed in the Flue Gas DCC was sent to the water treatment for disposal, the recycle case considered recycling the flue gas condensate to be used in the steam cycle. This has potential to reduce the demineralised water make-up by 75% and reduce the OPEX. Further evaluation is required in the next stage of engineering to assess the expected contaminants levels in the flue gas DCC condensate and its suitability to be used in the steam cycle.

Carbon Balance

The carbon balance for the plant is shows in Table 13. The carbon input to the plant consists of CO_2 in the SMR flue gas, CO_2 in the conditioning air and hydrocarbons in the natural gas for steam production. Carbon leaves the plant mostly as CO_2 product from the compression system, CO_2 in the stack gas and a small amount dissolved in the condensate.

Table 13. Carbon Balance

Carbon In		Carbon Out	
	lb/hr		lb/hr
SMR Flue Gas	88,494	Stack	8,012
Conditioning 1	242	CO2 Product	98,606
Conditioning 2	390	Purification Process Vent	223
Boiler Combustion Air	62	Product Conditioning Condensate	1
Natural Gas	18,593	Purification Condensate	3
Total	**107,780**	**Total**	**106,845**
		Error	0.009%

4.5 Consumables

CALF20 Solid Adsorbent Beds

The required CALF20 adsorbent volume for both RAMs can be seen in Table 14. The bed replacement period is 5 years.

Table 14. CALF20 SAB Volume

Description	Unit	
CO_2 Capacity	TPD	4346
Adsorbent Volume per RAM	m^3	145
Total Adsorbent Volume	m^3	290

4.6 Effluents and Emissions

A summary of the plant effluents and emissions can be seen in Table 15

Table 15. Plant Effluent and Emissions

Emissions/Effluents	Flow	CO_2, vol%	Trace Impurities	Remarks
Stack gas	5,186,317 lb/hr	0.4	CO, NO, SO2, NH3, CH4	Trace flue gas contaminants pass through to vent
Aux Boiler blowdown + quench	91 gpm	0.0	None	
Deaerator Vent	2,500 lb/hr		CO_2, NH_3	

Vent from CO_2 Purification	13,190 lb/hr	4	none	Dryer regeneration Gas
Structured Adsorbent	145 m3 / RAM per 5 yr cycle	N/A	None Expected	Adsorbent can potentially be recycled to reduce landfill quantity to zero
Cooling tower losses	1,600 gpm			
Cooling Tower Blowdown	265-750 gpm			
DCC Condensate	267 gpm			DCC condensate can be potentially recycled to PCC aux. boiler or cooling tower to reduce wastewater and water make-up requirements

General

The Svante Carbon Capture system does not generate additional hazardous air emissions than those contained in the host flue gas. The stack gas exhausted from the carbon capture system is primarily N_2, O_2 and H_2O, and air from the conditioning steps. Solid adsorbents, like CALF-20 , have inherent advantages over liquid amine systems which exhibit solvent loss through evaporation and carryover as well as degradation during operation. Solid adsorbents are made of non-hazardous materials, do not generate waste by-products or fugitive emissions, and do not pose significant environmental, health, or safety risks, a significant advantage to operators of the systems. Structured Adsorbent Beds (SAB) associated with Svante's technology are made from micron size MOF particles coated in a carbon-based substrate, then stacked, packaged, and bonded inside fire resistance aramid/phenolic honeycomb fiber panels.

Emissions

Contaminants in the SMR and Auxiliary fired equipment flue gasses passing through the Direct Contact Cooler will pass through the RAM adsorbent beds and vent through the stack. The stack gas will comprise mostly of N_2, O_2, and depending on the final contaminant levels in the flue gas, could potentially include trace amounts of NH_3, CO, NO, light hydrocarbons, etc. The nature of the flue gasses considered for this study are relatively low in contaminants such as SO_2 and NO_2**.**

Wastewater

To reduce overall make up water treatment requirements for the facilities, condensate streams produced at various stages of the process will be collected and recycled where possible. Clean condensate streams will be segregated for re-use in boiler water make up streams. Streams from the flue gas DCC will be sent to the wastewater system. Suspended solids from the stream will be filtered, the dewatered filtrate will be trucked off-site for disposal. Clarified water will be returned to the Refinery for re-use. Other wastewater sources include boiler and cooling tower blowdown streams.

Solid Waste

The Svante sorbent materials are classified as non-hazardous and can be disposed of in a licensed industrial waste site and in conjunction with state and federal rules. However, recent laboratory scale testing has shown that the adsorbent can be effectively recycled. This testing suggests that recycling has the potential to reduce solid waste disposal to zero.

4.7. List of Equipment

The summary list of key mechanical equipment of the Svante's CO_2 separation plant and Linde's CO_2 compression and purification plant as well as balance of plant are provided in the following tables.

Table 16. Equipment List – Base CCS Case

Equipment Description	# of Units
RAM (URSA 2000)	2
Hot Drains Sump	1
Blowdown Vessel	1
Conditioning 1 Air Blower	1
Conditioning 2 Air Blower	1
Conditioning 1 Air Inlet Filter	1
Conditioning 2 Air Inlet Filter	1
Conditioning 1 Direct Contact Cooler	1
Conditioning 1 Heat Exchanger	1
Conditioning 2 Heat Exchanger	1
Flue Gas Condensate Heat Exchanger	1

Conditioning 1 Dcc Condensate Cooler	1
Flue Gas Dcc Condensate Pump	1
Conditioning 1 Dcc Condensate Pump	1
Smr Flue Gas Blower	1
Boiler Flue Gas Blower	1
Cems Enclosure	1
Flue Gas Dcc	1
Vent Stack	1
Low Pressure Boilers	3
Low Pressure Boiler Deaerator	1
Boiler Fd Fans	3
Boiler Feed Pumps	4 (1 spare)
Product Blower	1
Product Separator	1
Product Cw Cooler	1
Reflux Blower	1
Dryer	1
CO2 Compressor Train	1
Refrigerant Compressor Package	1
CO_2 purification Package	1
Vent Gas PSA	1
Cooling Tower	1
Cooling Water Pumps	4 x 33%
Cooling Water Side stream Filter	1
Water Treatment System	1
Instrument Gas Unit	1
Wastewater Sump	1
Wastewater Sump Transfer Pump	2 x 100%
Wastewater Lift Station Pump	3 x 100%
Oily Water Separator and Lift Station	
Oily Water Separator Lift Pump	3 x 100%

5. Environmental, Health and Safety Risk Assessment

The post combustion CO_2 capture (PCC) process considered in this project will use solid adsorbents. This process is not expected to release any new hazardous chemicals from the adsorbents to atmosphere. This section summarizes results of an environmental, health, and safety (EH&S) risk assessment.

5.1 Emissions and Effluents

The estimated emissions in this section are for base CCS case operating at 100% rate.

Treated Flue Gas from RAM Units (05/06B)

Since Svante Carbon Capture technology requires steam, additional SOx, NOx, CO and VOC emissions are generated from the PCC auxiliary boilers that are installed to produce steam. The stack gas exhausted from the carbon capture system comprises treated flue gas and conditioning air streams and it contains primarily N_2, O_2, moisture, residual CO_2 and trace impurities present in the flue gas streams from the SMR and PCC auxiliary boilers.

Estimated new emission amounts are provided below. Detailed documentation will be required to prove this expected content for permitting and stack testing must occur within 6 months of plant start-up to document emissions.

NO and NO_2 Emissions

The PCC auxiliary boilers will generate additional NOx emissions. The Svante VeloxoTherm™ technology is expected to let most of NOx to pass through with the treated flue gas exiting to atmosphere through the stack.

NH_3 Emissions

Most of the ammonia in the combined flue gas feed from the SMR and auxiliary boiler (10 ppmv max.) will be removed in the DCC column and dissolved in the flue gas condensate.

SO_2 and SO_3 Emissions

The PCC auxiliary boilers will generate additional SOx from natural gas combustion. Due to the negligible SO_x content in the flue gas (expected << 1 ppmv), no additional treatment for SO_x removal is required upstream of the RAM units (05/06). The Svante VeloxoTherm™ technology in combination with direct contact cooler is expected to remove roughly 50% of SOx present in the flue gas.

VOC Emissions

The Svante VeloxoTherm™ technology does not produce any VOC compounds. Any VOC present in the flue gas will pass through the RAM with the treated flue gas exiting to atmosphere through the stack.

CO Emissions

The PCC auxiliary boilers are expected to produce minimal additional CO emissions. The Svante VeloxoTherm™ technology will not adsorb CO. As a result, all of the CO in the flue gas streams will be in the treated flue gas exiting through the stack.

Particle Emissions

The PCC auxiliary boilers will generate additional particle emissions from natural gas combustion. This is expected to increase the particle emissions by 34% over the amount present in the SMR flue gas. The process was not designed for particulate capture; however, a certain amount of particle matter will be removed from the flue gas in the DCC column (04). The adsorbent material will be adhered to the substrate in the metal organic framework structured adsorbent and is not expected to be released in operation. All particles entering the RAM are expected to pass through to the stack.

The incremental emissions associated with the PCC auxiliary boiler used for permitting purposes is given in Table 17. Annual emissions assumes operations at 8760 hours/year. For permitting purposes, calculations for hourly and annual values are performed using different factors as clarified in the footnotes of Table 17. As a result, annual values for some species do not align with hourly maximum values.

Table 17. Maximum PCC Boiler Flue Gas Emissions for Permitting

Component or Air Contaminant	Emissions	
	Hourly (lb/hr)	Annual TPY (Metric ton per year)
CO	32.70	28.07
NO_x	11.77	31.18
VOC	1.02	4.05
SO_2	0.47	1.87
$PM_{10/2.5}$	5.85	23.39
NH_3	0.0	0.0
Methanol	0.0	0.0

Notes:
1 For SO2, VOC and $PM_{10/2.5}$, same emission factors are used for both hourly and annual emissions.
2 The SO2 and PM values are estimated by applying AP-42.
3 The NOX and VOC emission factors are based on the expected performance on a short-term and annual basis with Selective Catalytic Reduction (SCR).
4 Hourly CO emissions are based on the TCEQ's BACT guideline for process heaters. Annual CO emissions are based on lower-than-BACT factor assuming that annual average CO emissions will be much lower than hourly maximum.
5. NOx emissions factors for hourly maximum and annual average 0.015 and 0.01 lb/MMBtu for, respectively.

MOF Adsorbent Replacement

The MOF structured adsorbent will need to be periodically replaced with a current estimated lifetime of 5 years. The adsorbent replacement volume is 145 m^3 equating to approximately 43,500kg of adsorbent. The structured adsorbent bed was classified as non-hazardous and would be disposed of at a licensed industrial waste site and in conjunction with State and Federal rules. Efforts are being made to recycle some or all of the MOF adsorbent in the structured adsorbent to reduce the solid waste disposal to zero. The MOF adsorbent will remain in the RAM unit with no particle emissions during the usage life.

5.2 Permitting Implications

The proposed project will be installed at the existing site. As a result, permitting analysis was carried out to determine changes needed to any of the existing permits.

The PCC Plant will take the entire flue gas stream from the SMR. The main sources of new emissions from the PCC Plant will be from the auxiliary boiler system. Those emissions are described in sections above. Due to new sources of emissions, permit amendment will be necessary for the host site. The PCC auxiliary boiler emissions would be expected to meet the current permitting requirements given below.

- NOx, annual average (lb/MMBTU HHV) 0.010
- Nox, hourly maximum (lb/MMBTU HHV) 0.015
- CO, maximum (lb/ MMBTU HHV) 0.009
- NH3, maximum (ppmv) 10
- VOC (lb/MMBTU HHV) 0.0013
- PM10/2.5 (lb/MMBTU HHV) 0.0075

The overall plant emissions summary document would be completed by Linde, then provided to a 3rd party consulting company. The 3rd party consultant would provide the expertise for completion of the permit application, including the textual description, analysis, QA/QC of the emission calculations and final submittal of the air permit modification application to the permitting agency.

We expect the entire permit amendment to take anywhere from 9 to 12 months for completion, pending no TCEQ issues or complications. After project is authorized, detailed information will be developed as part of the permit application, including any burner guarantees from the manufacturer for the auxiliary boiler and detailed documentation supporting the basis for the emission factors and data provided in the air permit application.

We are not expecting to exceed the LAER for any of the components of concern. This emissions permit is not expected to be a topic of risk or concern during project execution.

5.3. Structured Adsorbent Toxicological Effects

Solid adsorbents, like CALF-20 MOF, have inherent advantages over liquid amine systems which exhibit solvent loss through evaporation and carryover as well as degradation during operation. Solid adsorbents are made of non-hazardous materials, do not generate waste by-products or fugitive emissions, and do not pose significant environmental, health, or safety risks, a significant advantage to operators of the systems.

5.4 HAZID Study

A HAZID (Hazards and Operability Study) was conducted to ensure that the plant design is safe for operations. This study was led by an experienced 3rd party facilitator and supported by senior engineering representatives from Linde, Kiewit, and Svante. It uses a rigorous methodology used to qualitatively identify and address potential safety, health, environmental and asset risks. Following objectives were set:

- To systematically review the intended operation of the facility, and to analyze potential process safety and environmental hazards; specifically:
- To identify credible causes of incidents which could result in a release of highly hazardous materials
- The team will also note when a credible cause may lead to significant capital loss or major operational upsets (noted as equipment damage or operational issues only)
- To determine whether existing safeguards are adequate. If not, make recommendations to improve the design and/or operation of the process.

Various nodes on the P&ID were defined. Each node is a small portion of the process that includes one unit operation, typically on major process equipment with related piping and instrumentation or a complete system (e.g. compressor including a suction drum, intercoolers). For each node, deviations from normal operation for various process variables (flow, temperature, pressure, level, concentration etc.) were analyzed for possible consequences. As an example, deviations for flow may include more flow, less flow, no flow and reverse flow. Likely causes and consequences for each of the deviations were discussed to identify hazard scenarios without taking credit for any safeguards.

Severity and likelihood ratings were applied for each pair of causes and consequences. Based on these ratings, risk levels were identified for each hazard scenario and additional safeguards were incorporated in the design where needed.

In total 50 recommendations were made during the review. No “high potential” hazards requiring immediate attention were identified. These recommendations were either incorporated in the FEL-2 design or scheduled for further consideration during a FEED phase of the project.

6. Process Control

Due to the nature of the VeloxoTherm technology, control strategies for the main systems are relatively simple. The process controls pressure, temperature and flowrate of each of the individual streams entering and leaving the RAM. A high-level approach to controlling the system is discussed in the following sections, system inertia and capacitance impacts [depending on number of RAMs and duct arrangements and lengths] will be dynamically modelled in the next phase of study.

Several options were considered for integration of carbon capture facilities with the existing Linde SMR Hydrogen Production plant in US Gulf Coast. This review centered on selecting an economic solution with limited impact on continuing SMR operations. The configuration selected as the basis of design is as shown below.

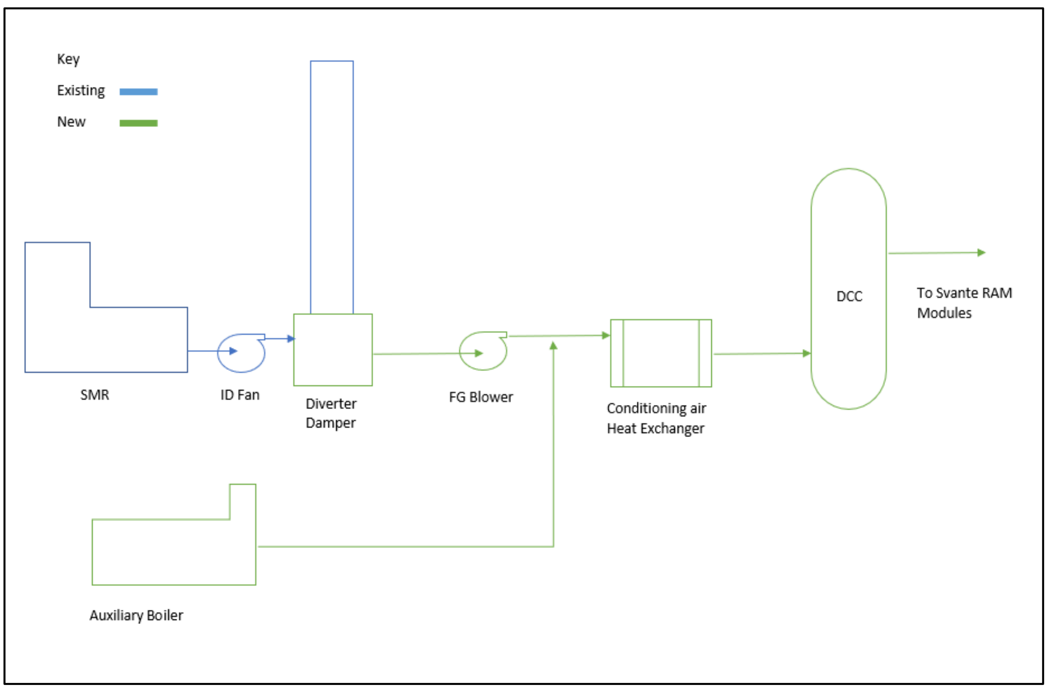

Figure 10. Integration of Capture Plant with existing SMR

The study assumed that the flue gas tie-in will be at the base of the existing stack and stack will remain open to the atmosphere. The PCC Auxiliary boiler flue gas will be bled into the system downstream of the new SMR flue gas blower to ensure limited impact of the SMR operation.

6.1 Flue Gas Blower Control

System flow is controlled by inlet guide vanes on the blower. A feed forward signal from the SMR combustion system will be used as principal flow control signal with feedback from blower inlet flow meter and flue gas composition. The detailed control strategy should be investigated in the next stage of the study.

The blower is provided with motor and fan bearing temperature monitoring and alarms.

Pressure transmitters upstream and downstream of the blower are used to monitor pressure rise across the blower, the downstream pressure transmitter monitors pressure and will be used in the fan inlet guide vane control logic.

An isolation damper provides unit isolation and inhibits backflow to the existing SMR system. This damper is provided with a seal air system. Flow is measured in the straight run of duct up-stream of the blower. This flow is added to the boiler flue gas flow and used for proportional flow control of all downstream systems.

6.2 CO_2 Product Control

The product RAM pressure is controlled by inlet guide vanes on the fan inlet. The controller will use the RAM A and RAM B outlet pressure to control the system pressure and output a signal to the fan guide vane positioner.

The outlet duct from each RAM currently has a damper to provide unit isolation, using this damper for independent pressure control on the outlet of each RAM will be investigated in the next stage of engineering.

A differential pressure transmitter across the blower and a pressure transmitter in the downstream duct will monitor and alarm high system pressure drop/high-low discharge pressure.

6.3 PCC Auxiliary Boilers and Steam System Controls

Auxiliary Boilers

During start up and shut down or during periods of low steam demand, the boiler units will be started/stopped manually by plant operators in response to overall plant steam demand. Once in operation, each unit will be placed in automatic mode. The operating units will run in parallel to maintain steam header pressure and steam flow demand from the capture plant.

The 3 boilers are fed separately from a single boiler feedwater header, drum level is the principal method of maintaining BFW flow to each boiler. 3-element control [drum level, steam flow, feedwater flow] is used to control the drum level control valve.

The boiler burner management/firing system will control the forced draft fan, FGR and fuel gas valves. Dry LoNOx combustion has been selected for emission control of the units. An inline flue gas analyzer will be used to monitor the composition of the combined flue gas stream.

Steam Export to Capture Plant

The main steam header system distributes steam to each of the 2 RAMs and pegging steam to the Deaerator. Each RAM has 2 steam steps, Product Steam and Reflux steam, each requiring an independent pressure reduction/desuperheater station [total 4 control stations]. For each control station, main steam pressure is let down by an independent pressure control valve. Spray water fed from the boiler feedwater header is injected to the steam path to control temperature by a control valve/nozzle arrangement to maintain the temperature setpoint.

A flow meter in each steam line provides feedback to the control system to maintain the required ratio of steam to CO_2 in the flue gas stream to the RAM. This flowrate can be controlled automatically or manually by operations personnel. Temperature measured at the RAM discharge provides the ability to trim steam flow rates to optimize performance.

6.4 CO_2 Purification and Compression Control

Flow into the system will be controlled via inlet guide vanes on the raw CO2 compressor packages. Due to the complexity of the compression equipment planned, vendor supplied PLC will be leveraged including both anti-surge and performance control.

Drying of the gas will be via a two-bed regenerative system. One of these beds will be online while the second is in regeneration. The onstream, heating, cooling, and standby times for this cycle will be defined based on design of the system and monitored via a process moisture analyzer to ensure proper performance of the system.

The rectification portion of the system will have multiple control loops maintaining proper levels, pressures, and temperatures for optimal performance of the system. One such critical control loop is the pressure of the vent out of the distillation column. Using a pressure transmitter on the vent line, a control valve will hold back pressure on the upstream process units in the plant. Other critical control loops in the rectification portion are related to the refrigeration system. Critical levels and pressures will be maintained in heat exchangers and process vessels to ensure adequate refrigeration is provided to the system.

The PSA unit is controlled by a special control software which ensures overall process operation. The control program is responsible for: step initialization, control of all switching and control valves, and process timing based on capacity and turn down.

Product compression will be controlled in a similar manner to the raw CO2 compressor package including, inlet guide vanes on the suction side of the machine and fast acting controller on a CO2 vent on the discharge side.

7. Constructability Review and Layouts

7.1 Introduction

The site selected as the basis of this study is the existing Linde H_2 facility, which is located on land within an existing refinery complex. The location of the new carbon capture facilities will be on the plot adjacent to the existing SMR.

7.2 Site Description

The area designated for the project will accommodate all major systems required for the carbon capture plant. However, due to the location of the site within the refinery complex, certain construction and logistical activities have been identified as requiring special consideration if this site is considered for future phases of development. The site is bounded by existing SMR and refinery infrastructure on 3 sides and by railroad and by a body of water on the 4th side.

The project execution plan benefits from methodologies developed for two construction projects performed within this area of the refinery complex, Linde SMR (in 2011) and the Linde PSA facility (currently under construction). This has meant that existing geotechnical and logistical information and successful implementation strategies developed with the refinery owner have been adopted. These strategies may add an element of risk and/or may result in added cost to the project. These are discussed in more detail below and have been recognized as risks to be fully evaluated in the next phase of the project.

7.3 Plot Plan – ISBL

Figure 11 provides the area plot plan for the Svante Capture Plant PCC Auxiliary Boilers (ISBL). This figure identifies and locates key packages.

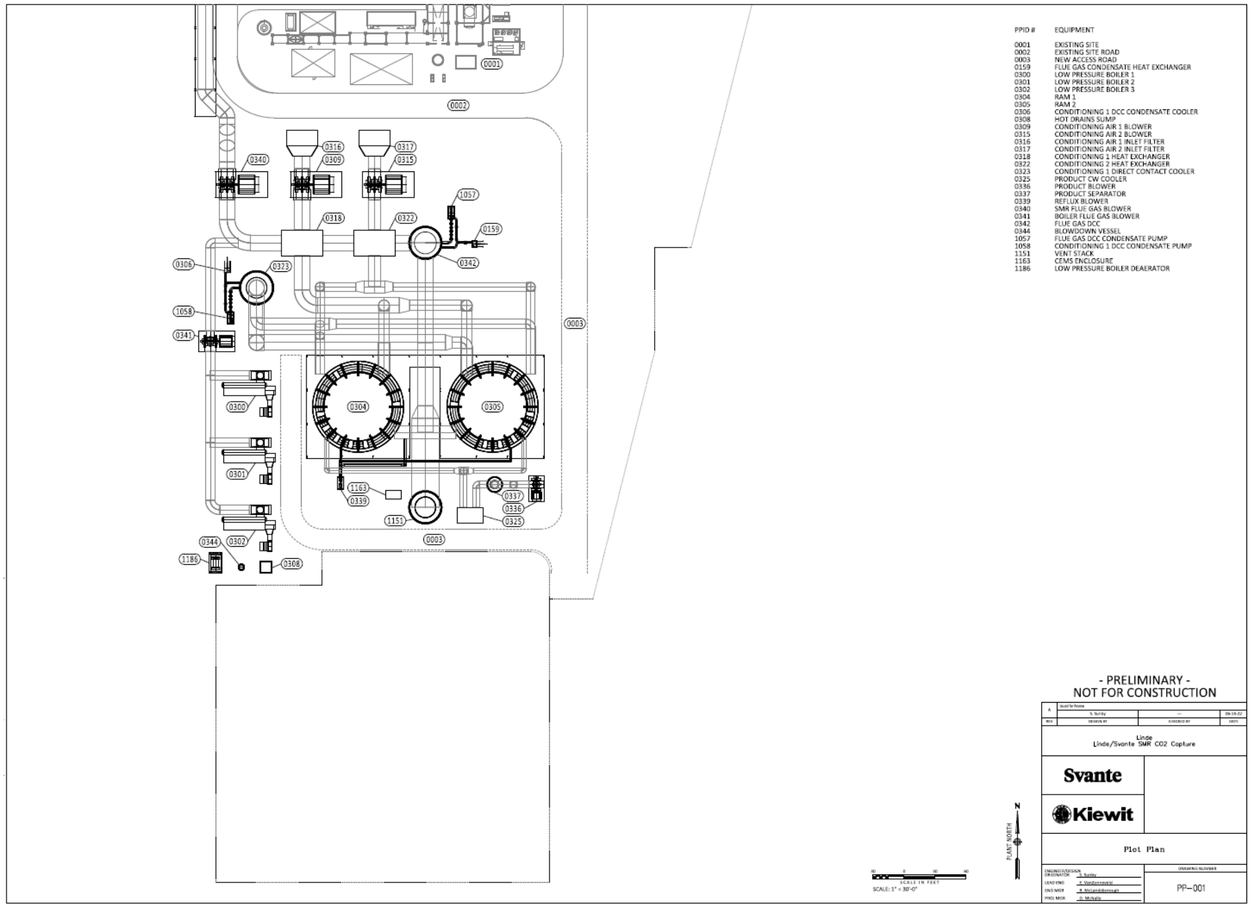

Figure 11. Core Plant (RAM) Plot Plan

7.4 Site Plan

Figure 12 provides the site plan for the project. This details the route for the flue gas duct, the area boundaries for the project and the tie-ins identified between the ISBL/OSBL and between the project and existing refinery systems. It can be seen from the site plan that existing SMR and refinery access roads have been maintained to limit impact on existing facility operations. Layout and optimization of equipment locations was performed in a 3D modelling format, views from the 3D model have been included at the end of this section.

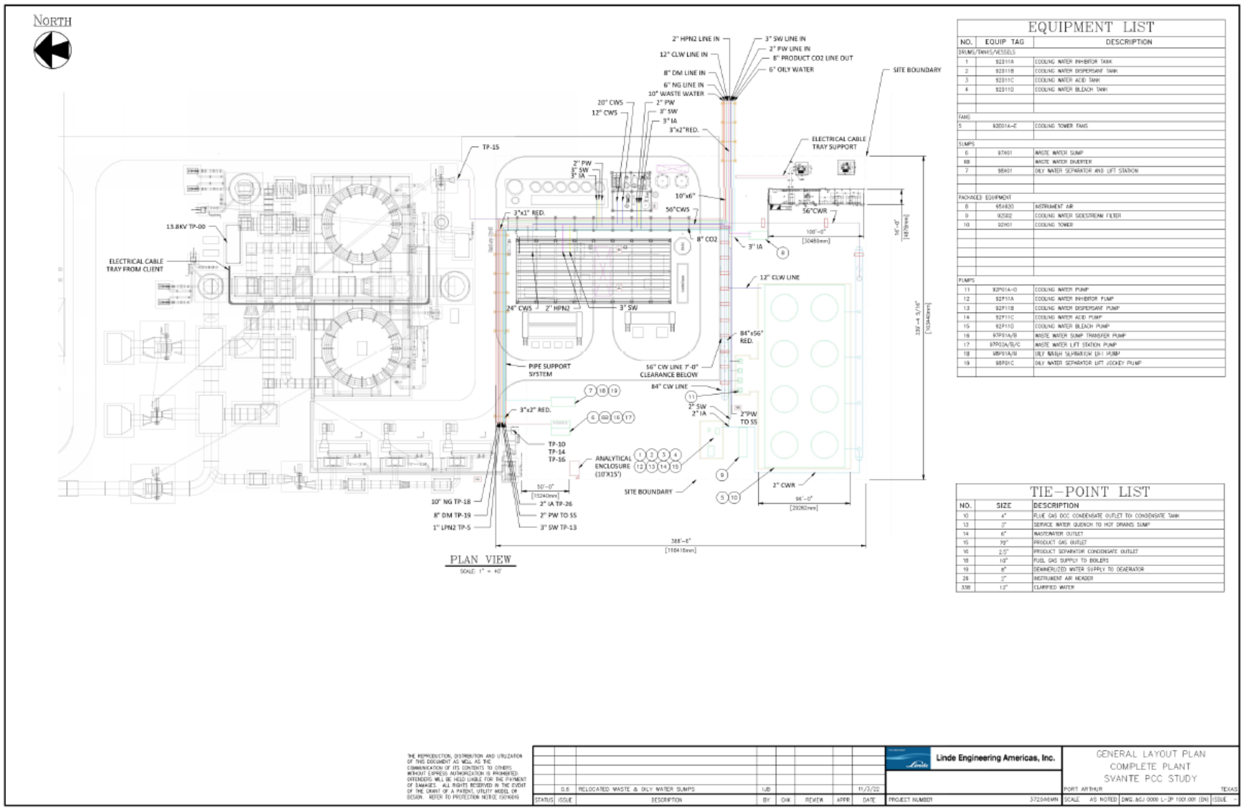

Figure 12. Overall Plant Plot Plan

7.5 Construction Execution

As noted in the site description, although adequate space has been assigned for the new carbon capture plant, access to the site must recognize limitations imposed by the location within the existing refinery complex and interface with existing plant infrastructure. The study is based on the following assumptions:

1. Contractor parking area will be outside the refinery and daily bussing to and from the work areas will be evaluated at the next stage of evaluations. The impact on labor costs and productivity will be evaluated in future phases of the project.
2. Construction laydown areas, warehousing, and site offices will be located adjacent to the work area.

Additional area for these construction activities may be required, however it is anticipated that any additional area can be acquired from the refinery owner. This will be addressed in detail in the next phase of the project, currently it is identified only as a construction risk.

3. A temporary construction power supply has been identified adjacent to the carbon capture plant site. This power supply was installed to support previous SMR and PSA projects and is assumed adequate for the carbon capture project construction demand of 2MVA.
4. The study assumes that project personnel entering the site will operate under refinery safety rules and will maintain required site-specific training and security certification. The impact on labor costs and productivity will be evaluated in future phases of the project. The site designated for the carbon capture facilities will be fenced, construction activities performed within this fenced area will be subject to contractor's safe work practices and permitting procedures.

   Work performed outside this fenced area will meet operating company requirements and will be controlled under their permitting procedures. This includes work required for tie-in to existing refinery and SMR systems which include for example, electrical, storm water and process drains, flue gas exhaust, make up water and other miscellaneous systems. Interconnection to existing systems will be coordinated with operating plant turnaround activities where possible. Certain activities may need to be performed outside such operational outages; these activities will be planned in detail and scheduled with plant operations. Due to the difficulty in estimating with accuracy current plans for scheduled maintenance outages, the study assumes that an SMR outage of sufficient duration will fall within the overall project schedule.
5. Site geotechnical conditions used for the study rely on recent geotechnical reports and recommendations. Area specific soils data and civil and foundation design criteria will be confirmed during the next phase of the project.

Due to the nature and ownership of the area designated for carbon capture plant, site clearing and preparation work will be performed by the refinery owner prior to mobilization for project construction activities. The construction area will be "bath-tubbed" and back filled with structural fill. This work will be performed in conjunction with the construction and operating project stormwater pollution prevention plan which will direct stormwater collected or discharged to the existing refinery collection systems.

Installation of driven piling, foundations and underground services will be sequenced with the site back-fill activities. Cost for laser scanning the existing site for tie in design and construction of flue gas duct is included. Cost for potholing the land is included as discussed in the basis of estimate to ensure no existing utilities are hit prior to construction.

The estimate assumes structured dewatering during construction is not required and has not been included. Groundwater is assumed to be at a depth that will not affect UG construction activities. Only "incidental" dewatering to manage precipitation events is considered.

6. The general philosophy for fabrication of structural and mechanical systems is to modularize to the maximum practical extent. The study relies on transportation and logistics work prepared for recent construction projects and uses where possible the size limits established in this route study for road-haul to the refinery and within the refinery to the project area. This results in a relatively limited opportunity for modularization since road transportation restrictions for major equipment and prefabricated multi- discipline modules reduce the extent of off-site work that can be performed. This will increase the construction labor hours to be expended on site and will demand careful sequencing of construction activities for major components/systems including RAMs, CO2 purification and compression and plant cooling water systems. Preliminary construction planning for the site suggests "inside-out" assembly of the mirrored RAMs, sequenced with duct installation and flue gas conditioning systems and steam generation plant. The CO2 purification and compression

system building will be constructed “just-in time” for delivery of major equipment. The cooling water tower will be purchased on a “supply and erect basis”, subcontractor work will be coordinated by the EPC contractor. The circulating water systems will be constructed in parallel with the cooling tower and CO2 conditioning and compression systems. This is a preliminary approach and as a final site location is identified and a FEED or more detailed study is developed, this plan will be refined, incorporating current lead times based on supply chain status at the time. Transformers and PDCs will be constructed in a “just-in time” and may potentially be the critical path schedule items. Preliminary construction planning indicates that there is adequate area for laydown and material handling equipment for this approach. However, this has been identified as an area of project risk to be further evaluated during the next phase of the project.

It is assumed that the two 13.8kV feeds are adequate to provide the capture plant power demand, and no substation redesign or investigations are needed at this time. KSI and Linde’s electrical system and pipe routing and sizing approaches have been developed independently for this effort, and some optimization of systems and equipment may be realized in future studies of further detail.

7.6 Systems Completion and Start-up

Preparation for systems completion, commissioning and facility turnover will commence during the FEED phase of the project. Work packaging will commence during early planning phases and will align with constructability requirements and completions sequencing. This will ensure that focus is maintained on process safety throughout the project and will continually assess start-up and operational risks associated with integration of the new carbon capture plant with existing operations.

Systems completion and start up activities fall into three phases, with completions and commissioning gate approval process will be agreed to in the FEED stage. The three phases considered for Completions activities are as follows:

1. Construction completion of systems.

2. Pre-commissioning activities.

3. Hot Commissioning/Functional Testing.

7.7 3D model views

Snapshots from the project 3D model can be seen in Figure 13 and Figure 14 below.

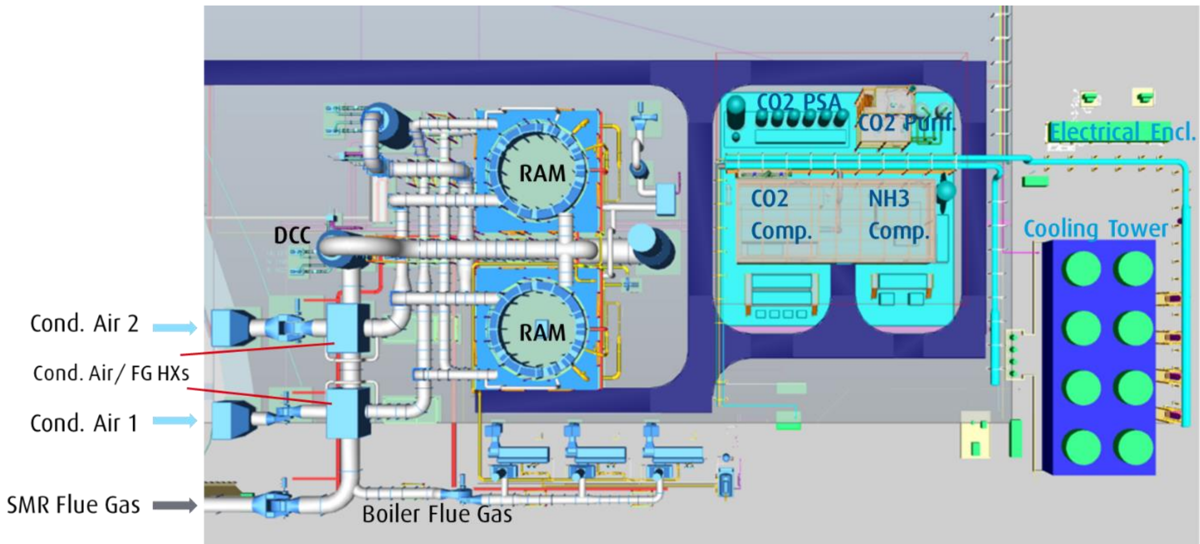

Figure 13. Plan View of PCC Unit from 3D Model

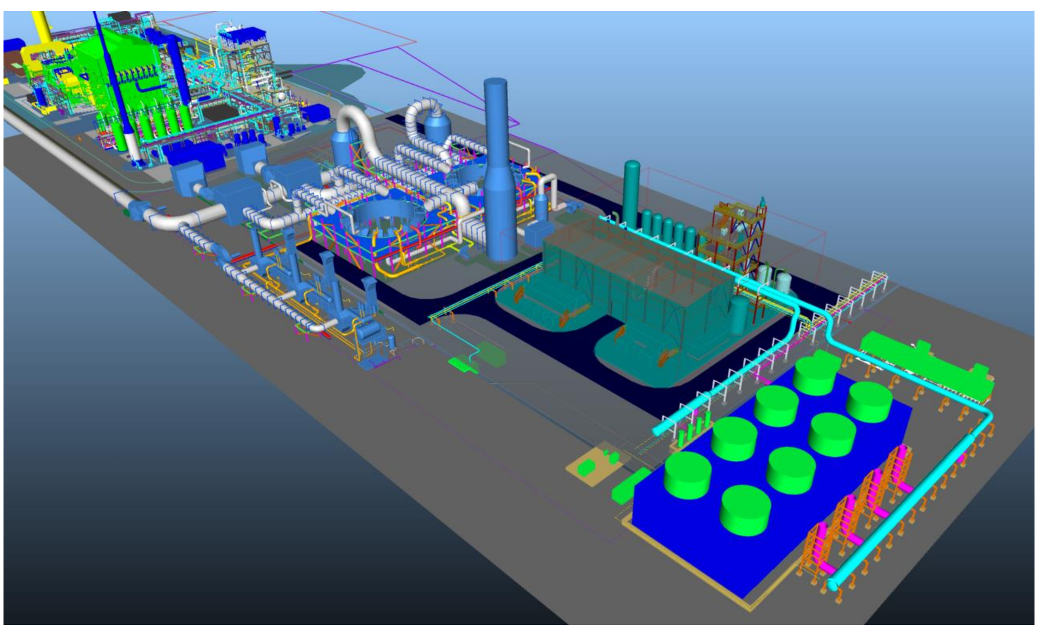

Figure 14. Isometric View of SMR and PCC Unit

8. Process Design – Step-Off Cases

8.1 Step-Off Case 1 – Catox Case

Block Flow Diagram

First step-off case involved using catalytic oxidation (Figure 15) instead of distillation to achieve <10 ppm O2 in purified CO_2. Svante's CO_2 separation plant configuration is the same as in the base case.

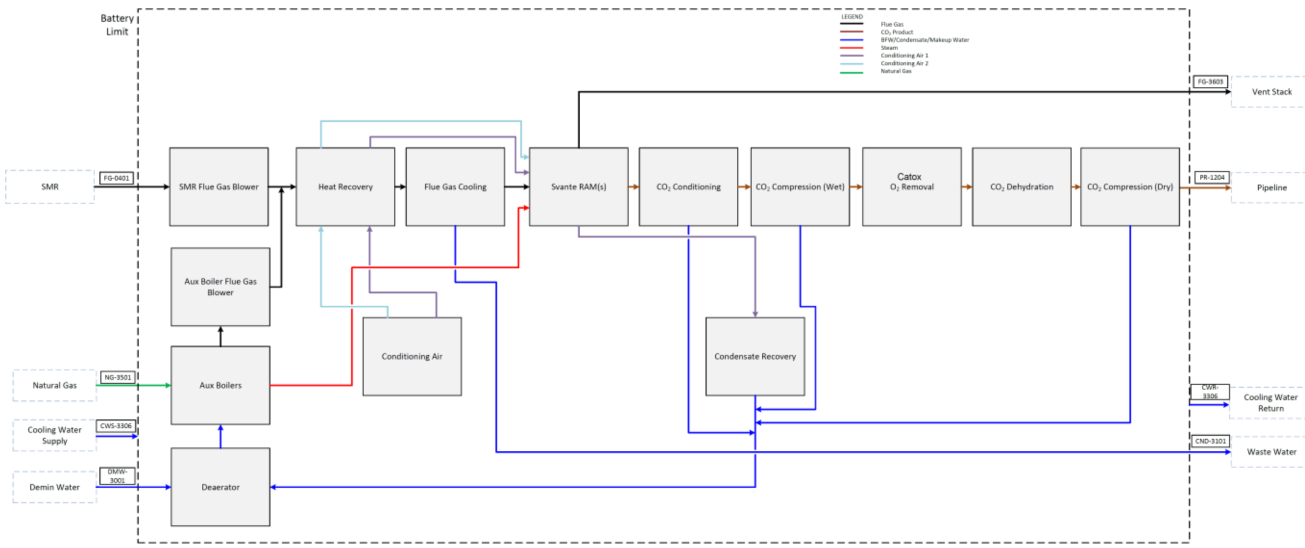

Figure 15. BFD – Svante Catox Case

Process Description

The CO_2 purification and compression process was significantly simplified. Referring to Figure 15, raw CO_2 from RAM is compressed to 30 bar in wet compression stages of the CO_2 compressor train and any condensed water is separated. The compressed raw CO_2 is sent to the Catox skid. The Catox skid includes a heat exchanger, a Catox reactor and a cooler. The raw CO_2 is preheated to 100 °C against effluent from the Catox reactor and then fed to the reactor. Reaction between injected hydrogen and raw CO_2 reduces O2 content in the effluent to <10 ppm. The effluent is cooled to remove condensate. The purified CO_2 is sent to the dryer for residual moisture removal. The dried CO_2 is compressed to 150 bar in dry compression stages.

Heat and Mass Balances

Heat and mass balances are presented in Table 18.

Table 18. Stream Summary for the Catox Case

		FG-0401	NG-3501	CWS-3306	DMW-3001	FG-3603	PR-1204	CWR-3306	CND-3101				
V-L Mole Fraction		1.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000				
CO2		0.1622	0.0186	0.0000	0.0000	0.0041	0.9601	0.0000	0.0000				
H2O		0.1785	0.0000	1.0000	1.0000	0.0747	0.0006	1.0000	1.0000				
N2		0.6411	0.0027	0.0000	0.0000	0.7672	0.0393	0.0000	0.0000				
O2		0.0182	0.0000	0.0000	0.0000	0.1540	0.0000	0.0000	0.0000				
CH4		0.0000	0.9630	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000				
C2H6		0.0000	0.0121	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000				
C3H8		0.0000	0.0036	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000				
H2		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000				
Total		1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000				
V-L Flowrate	kgmol/hr	20,604	693	974,642	4,316	87,589	3,871	974,642	3,399				
V-L Flowrate	kg/h	595,363	11,687	17,558,280	77,755	2,447,650	167,878	17,558,280	61,246				
Temperature	°C	149	16	32	60	68	49	40	59				
Pressure	kPa(g)	0.0	144.8	451.3	34.5	0.0	15,292.0	351.3	392.5				
Density	kg/m^3	0.81	1.72	1,002.44	982.93	0.97	563.72	996.08	981.77				
V-L Molecular Weight	kg/kgmol	18.0	18.0	18.0	28.7	28.7	28.7	28.7	28.7				
Mass Enthalpy	kJ/kg	-3562	-4817	-15820	-15674	-657	-8897	-15783	-15700				
V-L Flowrate	lbmol/hr	45,424	1,528	2,148,716	9,515	193,101	8,535	2,148,716	7,495				
V-L Flowrate	lb/hr	1,312,549	25,766	38,709,335	171,420	5,396,139	370,106	38,709,335	135,024				
Fuel Flowrate	lb/hr	-	-	-	-	-	-	-	-				
Temperature	°F	300	60	89	140	154	120	104	137				
Pressure	psi(g)	0.0	21.0	65.4	5.0	0.0	2217.3	50.9	56.9				
Density	lb/ft^3	0.05	0.11	62.58	61.36	0.06	35.19	62.18	61.29				

Utilities

The total utilities demand is summarized in Table 19. The power consumption decreased significantly (~15%) in this case due to elimination refrigeration compressor and simpler more efficient CO_2 compressor design as a result of elimination of recycle streams.

Table 19. Overall Utility Summary – Catox Case

Utility	Unit	Value
Natural Gas	MMBtu/hr (HHV)	600
Demin Water	US gpm	339
Clarified Water	US gpm	2,475
Electric Power Usage	kW	44,545
Cooling Water Circulation Rate	US gpm	76,900

List of Equipment

The equipment list for the Catox case is in Table 20. Equipment needed in the CO_2 separation and OSBL area are same as in the base CCS case. The CO_2 purification is the area where equipment was changed.

Table 20. Equipment List – Catox Case

Equipment Description	# of Units
Svante CO_2 Separation and PCC Aux. Boilers	
RAM (URSA 2000)	2
Hot Drains Sump	1
Blowdown Vessel	1
Conditioning 1 Air Blower	1
Conditioning 2 Air Blower	1
Conditioning 1 Air Inlet Filter	1
Conditioning 2 Air Inlet Filter	1
Conditioning 1 Direct Contact Cooler	1
Conditioning 1 Heat Exchanger	1
Conditioning 2 Heat Exchanger	1
Flue Gas Condensate Heat Exchanger	1
Conditioning 1 Dcc Condensate Cooler	1
Flue Gas Dcc Condensate Pump	1
Conditioning 1 Dcc Condensate Pump	1
Smr Flue Gas Blower	1
Boiler Flue Gas Blower	1
Cems Enclosure	1
Flue Gas Dcc	1
Vent Stack	1
Low Pressure Boilers	3
Low Pressure Boiler Deaerator	1
Boiler Fd Fans	3
Boiler Feed Pumps	4 (1 spare)
Product Blower	1
Product Separator	1
Product Cw Cooler	1
Reflux Blower	1
CO_2 Purification and Compression	
CO2 Compressor Train	1
Catox Skid	1
Dryer	1
OSBL	
Cooling Tower	1

Cooling Water Pumps	4 x 33%
Cooling Water Side stream Filter	1
Water Treatment System	1
Instrument Gas Unit	1
Wastewater Sump	1
Wastewater Sump Transfer Pump	2 x 100%
Wastewater Lift Station Pump	3 x 100%
Oily Water Separator and Lift Station	
Oily Water Separator Lift Pump	3 x 100%

8.2 Step-Off Case 2 – Energy Optimization Case

Block Flow Diagrams

This case included significant changes in all the areas of the CO_2 capture plant with regards to heat integration in order to optimize energy consumption. A Block flow diagram for the Svante's CO_2 separation process and Svante's compression and purification process is shown in Figure 16.

Process Description

A series of heat exchangers are used to recover low-grade and high-grade energy by heating hot water in the hot water closed loop. Heat is recovered from the inlet flue gas prior to final cooling stage, the product CO_2 stream leaving the RAM and from the heat of compression from the CO_2 compression system.

The hot water leaving these heat exchangers is sent to a Flash Steam Vessel to generate steam by flashing. The flashed steam is sent directly to the RAM for adsorbent regeneration, while the condensate is recirculated back to the exchangers. Required make-up water to generate flash steam is supplied through BFW from the BFW pumps.

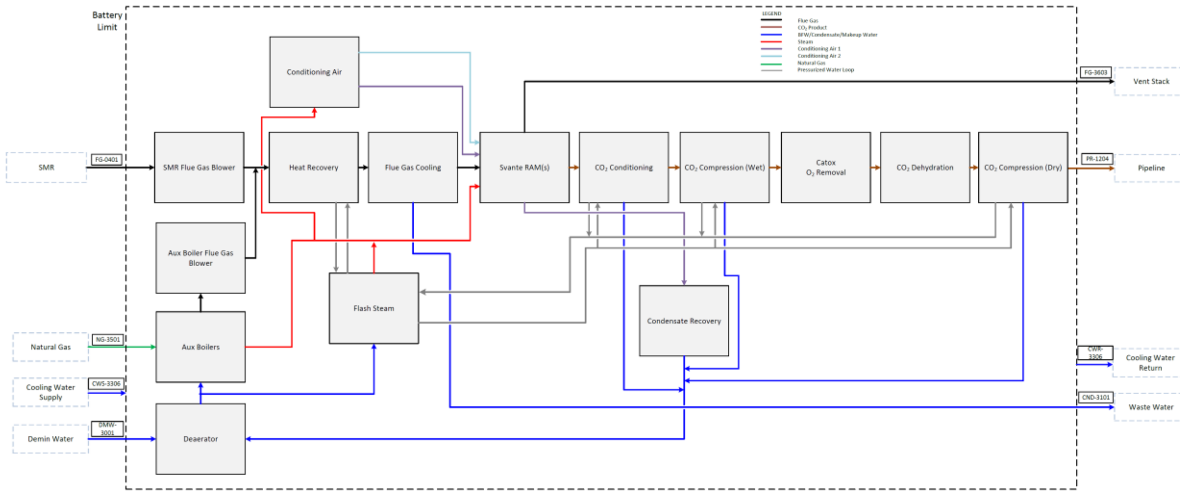

Figure 16. BFD – Svante Energy Optimization Case

Heat and Mass Balances

Heat and mass balances are presented in Table 21.

Table 21. Stream Summary for the Energy Optimization Case

		FG-0401	NG-3501	CWS-3306	DMW-3001	FG-3603	PR-1204	CWR-3306	CND-3101				
V-L Mole Fraction		1.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000				
CO2		0.1622	0.0186	0.0000	0.0000	0.0042	0.9599	0.0000	0.0000				
H2O		0.1785	0.0000	1.0000	1.0000	0.0747	0.0006	1.0000	1.0000				
N2		0.6411	0.0027	0.0000	0.0000	0.7666	0.0395	0.0000	0.0000				
O2		0.0182	0.0000	0.0000	0.0000	0.1544	0.0000	0.0000	0.0000				
TEG		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000				
H2		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000				
CH4		0.0000	0.9630	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000				
C2H6		0.0000	0.0121	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000				
C3H8		0.0000	0.0036	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000				
Total		1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000				
V-L Flowrate	kgmol/hr	20,604	526	758,007	3,971	82,150	3,708	758,007	3,157				
V-L Flowrate	kg/h	595,363	8,864	13,655,567	71,535	2,296,012	160,771	13,655,567	56,873				
Fuel Flowrate	kg/hr	-	-	-	-	-	-	-	-				
Temperature	°C	149	16	32	10	68	49	40	37				
Pressure	kPa(g)	0.0	144.8	451.3	30.0	0.0	15,290.8	351.3	342.5				
Density	kg/m³	0.81	1.72	1,002.44	999.54	0.97	563.54	996.03	998.64				
V-L Molecular Weight	kg/kgmol	18.0	18.0	18.0	18.0	28.7	28.7	28.7	28.7				
Mass Enthalpy	kJ/kg	-3562	-4817	-15820	-15884	-659	-8896	-15783	-15797				
V-L Flowrate	lbmol/hr	45,424	1,159	1,671,117	8,754	181,110	8,174	1,671,117	6,960				
V-L Flowrate	lb/hr	1,312,549	19,543	30,105,337	157,708	5,061,834	354,440	30,105,337	125,384				
Fuel Flowrate	lb/hr	-	-	-	-	-	-	-	-				
Temperature	°F	300	60	89	50	154	120	104	98				
Pressure	psi(g)	0.0	21.0	65.4	4.4	0.0	2217.2	50.9	49.7				
Density	lb/ft³	0.05	0.11	62.58	62.40	0.06	35.18	62.18	62.34				

Utilities

The total utilities demand is summarized in Table 22. Steam requirements from the auxiliary boilers was reduced by 25% as part of the steam needed for RAM was generated from heat of compression and from better heat integration in the CO_2 separation section. NG consumption was reduced as a result of the heat integration and the overall CO_2 captured frpm the auxiliary boiler flue gas was reduced. Cooling water demand was reduced by 25% mainly in CO_2 compression train as heat of compression was used for generating part of steam instead of rejecting the heat via cooling water. CO_2 compression power increased as some of the intercoolers were eliminated. Thus, part of benefit of fuel saving was offset by increase in power consumption.

Table 22. Overall Utility Summary – Energy Optimization CCS Case

Utility	Unit	Value
Natural Gas	MMBtu/hr (HHV)	450
Demin Water	US gpm	317
Clarified Water	US gpm	2015
Electric Power Usage	kW	45,430
Cooling Water Circulation Rate	US gpm	62,000

Equipment List

Equipment lists for the energy optimization case are in Table 23. Major differences in this case compared to the Catox are listed below:

- Heat exchangers for exchanging heat between flue gas and conditioning air streams are replaced by separate heat exchange coils within the flue gas and conditioning air ducts.
- Only two PCC auxiliary boilers are needed due to reduced steam demand from the boilers.
- LP steam generation system is added to generate steam using low grade heat. This system include water heaters integrated into the CO_2 compression train, pump for water circulation and flash vessel for generating low pressure steam.
- Capacity of cooling tower and water circulation pumps is ~25% lower due to lower overall cooling duty in the plant.

Table 23. Equipment List – Energy Optimization Case

Equipment Description	# of Units
Svante CO_2 Separation and PCC Aux. Boilers	
RAM (URSA 2000)	2
Hot Drains Sump	1
Blowdown Vessel	1
Conditioning 1 Air Blower	1
Conditioning 2 Air Blower	1
Conditioning 1 Air Inlet Filter	1
Conditioning 2 Air Inlet Filter	1
Conditioning 1 Direct Contact Cooler	1
Conditioning 1 Air Pre-Heater	1
Conditioning 1 Trim Air Pre-Heater	1
Conditioning 2 Air Pre-Heater	
Conditioning 2 Trim Air Pre-Heater	
Flue Gas Condensate Heat Exchanger	1
Conditioning 1 DCC Condensate Cooler	1
Flue Gas DCC Condensate Pump	1
Conditioning 1 DCC Condensate Pump	1
SMR Flue Gas Blower	1
Boiler Flue Gas Blower	1
CEMS Enclosure	1
Flue Gas DCC	1
Vent Stack	1
Low Pressure Boilers	2
Low Pressure Boiler Deaerator	1
Boiler FD Fans	2
Boiler Feed Pumps	3 (1 spare)
Product Blower	1
Product Separator	1
Product CW Cooler	1
Product Water Heater	1
FG/Condensate Heater	1
Flue Gas Water Heater	1
Reflux Blower	1
CO_2 Purification and Compression	
CO2 Compressor Train	1

Catox Skid	1
Dryer	1
LP Steam Generation System	1
OSBL	
Cooling Tower (6 cells)	1
Cooling Water Pumps	4 x 33%
Cooling Water Side stream Filter	1
Water Treatment System	1
Instrument Gas Unit	1
Wastewater Sump	1
Wastewater Sump Transfer Pump	2 x 100%
Wastewater Lift Station Pump	3 x 100%
Oily Water Separator and Lift Station	
Oily Water Separator Lift Pump	3 x 100%

9. CAPEX Estimate

9.1 Methodology

Capital costs were estimated with +/- 20% accuracy for the base CCS case and with +/-30% accuracy for the two step-off cases. It was assumed that equipment can be procured from anywhere in the world and global engineering resources from all involved companies can be used. The cost estimate was prepared by Kiewit and Linde according to scope split described below.

General Approach

The purpose of the capital cost estimate during FEL-2 is to generate an AACE class IV estimate cost as defined with listed deliverables in Table 24. The basis of estimate covers the carbon capture plant for the Linde SMR hydrogen plant, including the Svante VeloxoTherm™ process equipment and associated Inside the Battery limit (ISBL) scope, the CO_2 purification and compression system and the supporting BOP systems located Outside the Battery Limit (OSBL).

Table 24. Cost Estimate Class Definition

Engineering Association	Definition	Deliverables	Status
IPA Front End Loading (FEL)	FEL - 2	Block Flow Diagrams (BFDs)	C
AACE Designation (18R-97)	Class 4 Initial	Process Flow Diagrams (PFDs)	P
AACE Usage (18R-97)	Feasibility	Discipline Design Criteria	C

Scope Categories	Definition	Plot Plans	C
Estimate Accuracy Target	-15% to +20%	Utility Flow Diagrams (UFDs)	C
Project Contingency	10% to 15%	Piping & Instrument Diagrams (P&IDs)	P
Project Defined	10% to 20%	Equipment List	C
Estimation Methodology	Calculated	Electrical Single-Line Diagrams (SLDs)	C
Project Scope Description	Defined	Specifications & Datasheets	P
Plant Capacity	Defined	General Arrangement Drawings	P
Plant Location	Specific		
Site Conditions	Defined		
Integrated Project Plan	Defined		
Project Schedule	Level 3		
Legend - Preliminary (P): Work on deliverables is advanced, initial review complete. **Complete(C):** Deliverables have been fully reviewed and issued for construction (IFC)			
Note: Core technology modules will be developed to 'Complete (C)' status. Balance of plant modules and OSBL will be developed to 'Preliminary (P)' status.			

Kiewit estimated EPC (engineering, procurement and construction) costs for Svante's core equipment and steam generators and construction costs for OSBL areas, equipment, and buildings. Linde estimated EPC costs for CO_2 purification and compression system and EP costs for OSBL equipment (cooling tower, electrical equipment, and misc. utilities). Linde combined these estimates and adjusted overall process contingency (~7%) to develop overall EPC cost estimate. Linde then estimated owner's costs and applied appropriate project contingency (also 7%) to develop total overnight capital costs.

This carbon capture plant capital cost estimate has been prepared based on a Class IV Cost Estimate and developed the project definition roughly 10-15%. This project definition was increased through select deliverable development, 3D modelling, P&ID detail, high level equipment sizing, and structural calculations. The FEL-2 team was able to obtain current vendor quotations for boilers, blowers, and direct contact coolers. These were priced specifically for FEL-2 designs and represent a level of detail higher than other smaller equipment, which were priced using Kiewit's and Linde's robust, current, and applicable database of historical equipment pricing.

Combining Kiewit's and Linde's industry knowledge of local rates and costs to complete similar work with designed quantities, FEL-2 team can arrive at a highly accurate estimate for the carbon capture facility.

Equipment costs

Scope of equipment included all the ISBL and OSBL equipment, piping materials, instrumentation and controls, capital and operating spares and freight. A detailed equipment list (see section 2.2) was prepared from the process flowsheet and heat and mass balances. For major equipment, vendor quotes or recent proposals were relied upon. For certain smaller equipment, past references were used to estimate the costs. Cost estimate of RAM was developed by Svante. Vendor quotes were obtained for blowers, DCC, auxiliary boilers and cooling tower. The costs of equipment in CO_2 compression and purification section were estimated from similar sized equipment in other proposals. The electrical and controls equipment costs were estimated by both Kiewit and Linde, each estimating this cost for their supplied equipment scope. Overall integrated control system costs were estimated by Linde as these would be integrated into the control system architecture of the existing SRM. Freight costs were estimated based on logistics planning. List of spares needed was prepared and costs of spares were estimated.

Construction costs

The site-specific cost estimate has been prepared using known site conditions, 3D modelling and dimensioning, and existing geotech and utility information provided by Linde. The estimation methodology is a quantity-driven material take-off (MTO) estimate. The estimate uses current local labor rates and considers efficiencies gained through modularization, site laydown and layout availability, as well as brownfield considerations inside an operating facility. The FEL-2 team benefits from Kiewit's local recent experience in similar construction projects, leading to high accuracy in local labor rates, craft access, bussing, laydown, crane plans, and other logistic considerations. In addition, the feed flue gas interconnection duct and rack from the SMR stack to the carbon capture ISBL process train had structural and mechanical 3D modelling and quantity take-off, leading to a higher accuracy than a typical Class IV estimate for that specific scope. This effort details and refines the steel tonnage, concrete quantities, accessways, duct lengths, large bore pipe linear footage, electrical cable and duct runs, and other quantities for a higher accuracy cost estimate.

Engineering costs

Engineering resources were estimated by Linde and Kiewit for their respective scopes during different stages of project execution. Appropriate engineering labor rates were applied depending on which countries these resources are based in.

Owner's Costs

Owner's costs included costs for operations and commercialization support personnel, utilities consumed during start-up, permitting, property taxes, bringing utilities to battery limit and miscellaneous supplies.

Contingency costs

Contingency for the EPC scope was set at 7%. A separate project level contingency of 7% was applied to cover unforeseen changes in scope and customer requirements.

The total CAPEX built up using Linde's internal cost estimation methodology is equivalent to NETL's definition of total overnight cost (TOC).

Project Schedule

Total project execution duration from FEED kick-off to start-up is estimated to be 48 months. This includes ~12 months for FEED activities and ~36 months of project execution.

9.2 Capital Costs

The capital cost breakdown for the base CCS case and two step-off CCS cases are presented in Table 25. These estimates are in 2023 dollars. As mentioned earlier, the accuracy of estimate for the base CCS case is +/- 20% as this case was the main focus of the engineering design efforts. Two step-off cases were estimated with less engineering design details and as a result, they are likely to have lower accuracy of +/- 30%. Since large portions of sub-systems in step-off cases did not change, accuracy of estimate for those would be same as in the base CCS case.

Table 25. CAPEX Breakdown for the CCS Cases

CAPEX, $MM	Base CCS Case	Catox CCS Case	Energy Opt. CCS Case
Engineering	$37.5	$26.4	$24.7
Equipment	$157.7	$147.7	$138.3
Construction	$332.2	$260.8	$243.9
Process Contingency	$40.6	$33.0	$30.5
Subtotal EPC Costs	**$568.0**	**$467.9**	**$437.4**
Owner's costs	$41.7	$39.7	$38.8
Project contingency	$46.0	$38.4	$36.0
Total Overnight Costs (TOC)	**$655.7**	**$546.0**	**$512.2**

The CAPEX of the base CCS case was highest at $656 MM. Engineering and equipment costs were in line with expectations. Construction costs were higher than expected partly due to inflation in material and labor costs over last 2 – 3 years and partly due to significant field work required in the CO_2 purification and compression island due to complexity of process design.

The Catox case was pursued specifically with the objective of simplifying the CO_2 purification process. Svante and Linde teams contacted three different vendors for quotes. All of them indicated feasibility of achieving <10 ppm O2 spec for CO_2 purity. A quote from the vendor who was willing to provide skidded equipment was used in the cost estimate. Equipment costs for the CO_2 purification were significantly reduced due to elimination of refrigeration compressor, vent gas PSA and sub-ambient rectification system and simpler CO_2 compressor train. Construction costs for this simplified design were developed by Linde based on a recent proposal for a project similar in scope to the Catox case. It was a factored estimate using somewhat more conservative values compared to the commercial proposal mentioned above. Due to simpler purification process, significant reduction in engineering and construction costs for this section was realized. The total Capex for this case was ~17% lower compared to the base CCS case.

In the energy optimization case, equipment cost reduction estimated in the CO_2 separation section is from replacing flue gas to conditioning air exchangers with heating or cooling coils inside the flue gas and air ducts with water as working fluid to exchange heat. This change will simplify routing of those large size ducts as they do not have to cross each other for heat exchange. In addition, the costs of heat exchanger coils are estimated to be somewhat lower than large gas-gas exchanger used in the previous two cases. Other major reduction in cost is estimated in the OSBL equipment. One of the three Auxiliary boilers for steam generation is eliminated and cooling water system size reduced by ~25%. The cost of CO_2 compressor is estimated to be somewhat higher than the Catox case due to higher power consumption. Overall, the Capex is estimated to reduce by ~6% compared to the Catox case.

10 Technoeconomic Analysis

10.1 TEA Methodology

NETL's methodology for levelized cost was adapted for technoeconomic analysis [1, 2]. The levelized cost of CCS was estimated from CAPEX and OPEX estimates for the PCC unit. Real dollars are used as basis of all calculations. There are some differences in the approach used in this report vs. NETL methodology. These differences are noted where applicable. Two different scenarios for financing were evaluated. First scenario (A) is same as the one described in NETL's cost assessment on H2 production technology [1]. Second scenario (B) was defined based on 15 years project life and 100% equity financing. The cost of equity for Scenario B was assumed to be 7.84%, same as reported in NETL's QGESS for costs [2]. Details of calculations are provided in Appendix A. Table 26 summarizes key parameters for the TEA.

Table 26. Cost Estimate Assumptions for Two TEA Scenarios

	Scenario A	Scenario B
Project life	30	15
Debt	38%	0%
Equity	62%	100%
Capacity factor, %	90%	90%
Fixed costs, % of TOC/yr	3.3%	3.3%
TASC[2]/TOC ratio	1.07	1.14
Capex recovery factor, % of TASC/yr	6.02%	13.2%
LFP for NG, $/MMBtu HHV	$4.42	$4.17
Power, $/MWh	$71.7	$71.7
Water, $/1000 gal	$1.90	$1.90

10.2 Carbon Footprint Analysis

The CO_2 emission factors listed in Table 27 were used to estimate carbon footprint.

Table 27. Carbon Intensity Factors

Parameter	Emissions factor
NG direct Scope 1, kg CO_2/MMBtu HHV	53.7
Power, kg CO_2/kWh	0.4
NG Scope 3, kg CO_2/MMBtu HHV	12.77
Power Scope 3, kg CO_2/kWh	0.1

10.3 TEA Results

Carbon footprint results are summarized in Table 28. Total CO_2 generated in the base CCS case will increase due to addition of CO_2 generated in the auxiliary boilers. With CO_2 capture, Scope 1 emissions reduction of 90.4% will be achieved. Scope 3 emissions related to NG increases in the base CCS case in proportion to increase in NG consumption. The Catox case Scope 1 and NG related Scope 3 emissions are similar to the base CCS case. Only major difference in the Catox case is reduction of Scope 2 and power related Scope 3 emissions due to decreased power consumption. In the energy optimization case, major difference is decrease in NG related Scope 3 emissions due to reduced NG consumption in comparison to other two CCS cases.

If total carbon intensity without steam credit is considered, then the reduction achieved in the best CCS case (energy optimization) is 56%. Thus, 90% reduction in Scope 1 is offset by increase in Scope 2 and Scope 3 emissions resulting from parasitic load of NG and power.

Table 28. Carbon Intensity Summary

CI kg CO_2/kg H_2	No CCS	Base CCS Case	Catox Case	Energy Opt. Case
Scope 1	10.8	1.0	1.1	1.0
Scope 2	0.3	1.9	1.7	1.7
Scope 3	2.6	3.5	3.4	3.3
Steam export credit	-3.0	-3.0	-3.0	-3.0
Total with steam credit	**10.7**	**3.4**	**3.2**	**3.0**
Total without steam credit	**13.7**	**6.4**	**6.2**	**6.0**

The cost summary for the CCS cases for two scenarios A and B are presented in Table 29 and Table 30. All scenario B CCS costs are approximately 40% higher than Scenario A. Major difference is in Capex recovery component, which is affected by higher TASC/TOC ratio of 1.14 for Scenario B (vs. 1.07 in scenario A) and higher Capex recovery factor of 13.2% for Scenario B (vs. 6% for Scenario A). As a result, Capex recovery component of the CCS cost more than doubles in Scenario B. With current 45Q tax credit, it is more likely that projects will be financed with project lifetime of 15 years, the rest of cost comparison discussion is based on Scenario B.

Table 29. CCS Cost Breakdown for Scenario A

	Base CCS Case	Catox Case	Energy Opt. Case
TOC, $MM	656	546	512
TASC/TOC multiplier	1.07	1.07	1.07
TASC, $MM	**702**	**584**	**548**
LCOCCS breakdown, $/T CO_2			
CAPEX recovery	$32.7	$27.3	$26.7
Fixed O&M costs	$16.8	$14.0	$13.7
Variable costs	$43.9	$40.6	$38.1
T&S	$10.0	$10.0	$10.0
Total, $/T CO_2 captured	**$103.3**	**$91.8**	**$88.5**
Total, $/T Scope 1 CO_2 reduced	**$127.6**	**$113.6**	**$104.3**

The cost of CCS for the base CCS case is estimated to be $146/T CO_2 captured. The Capex recovery accounts for ~52% of this cost. Catox case is estimated to result in $127.5/T CO_2 captured, which is ~13% lower than the base CCS case due to ~17% Capex reduction and ~8% reduction in variable costs. Energy optimization case achieves further reduction of ~3% on the basis of per ton of CO_2 captured. This reduction seems smaller than expected considering the fact that Capex is reduced by ~6% and NG consumption is reduced by ~25%. The reason for this anomaly is reduction in amount of CO_2 captured along with the reduction in Capex and Opex. So, when costs are reported on per ton of CO_2 captured, reduction is smaller. The real improvement of the energy optimization case becomes apparent when comparing costs per ton of Scope 1 CO_2 emissions reduced. On this basis, the cost of CCS is decreased by ~8% from $157.7/T to $145.7.

Table 30. CCS Cost Breakdown for Scenario B

	Base CCS Case	Catox Case	Energy Opt. Case
TOC, $MM	656	546	512
TASC/TOC multiplier	1.14	1.14	1.14
TASC, $MM	**748**	**622**	**584**
LCOCCS breakdown, $/T CO_2			
CAPEX recovery	$76.6	$63.9	$62.6
Fixed O&M costs	$16.8	$14.0	$13.7
Variable costs	$42.9	$39.7	$37.3
T&S	$10.0	$10.0	$10.0

Total, \$/T CO_2 captured	**\$146.3**	**\$127.5**	**\$123.6**
Total, \$/T Scope 1 CO_2 reduced	**\$180.6**	**\$157.7**	**\$145.7**

Since main revenue source is likely to be the amount of CO_2 sequestered via 45Q tax credits, it is necessary to compare \$/T CO_2 captured. Since \$85/T CO_2 is a tax credit, on a pre-tax basis it is actually worth higher amount depending on the applicable tax bracket. On the other hand, it is available for only 12 years, its value for 15 years project is somewhat less. Considering these factors along with different financing scenario, it is conceivable that project could become financially viable at ~\$100/T CO_2 captured. Based on the cost projections from this study, significant further cost reductions are needed in both CAPEX and OPEX. Opportunities for improvement in variable costs are mostly in reducing power consumption by simplifying regeneration scheme for RAM and to a smaller extent from further reduction in steam requirements. In CAPEX, the cost of RAM is already very modest in comparison to the overall costs. So, improvement has to come from reduction in auxiliary equipment costs such as regeneration air system and duct work. If regeneration air requirement can be significantly reduced, then both CAPEX and OPEX can be significantly reduced. These optimization concepts are currently investigated by Svante in the various pilot and demonstration projects.

Summary

Preliminary engineering design of the Svante's adsorbent based post-combustion capture technology at Linde's existing SMR was completed. The base CCS case design used a single train with two RAMs (URSA 2000) for capturing 92% of CO_2 at >99.9% purity. At normal operating conditions, this plant will capture 3933 tpd CO_2 (~1.435 MM tpy). The capture rate of ~92% from combined flue gases of SMR and PCC auxiliary boiler corresponds to 90% reduction in Scope 1 CO_2 emissions compared to baseline SMR operation without CCS. The CAPEX of the plant was estimated to be $656 MM with +/-20% accuracy. Two step-off CCS cases were evaluated to reduce both CAPEX and utilities consumption. The Catox CCS case resulted in ~17% lower CAPEX, ~15% lower unit power and no change in NG consumption. The Energy Optimization CCS case, which incorporated better heat integration into the Catox case, resulted in further reduction of ~6% CAPEX and ~25% reduction in NG consumption while increase in ~6% unit power compared to the Catox case.

The cost of CCS for the base CCS case is estimated to be $146/T CO_2 captured. Catox case is estimated to result in $127.5/T CO_2 captured, which is ~13% lower than the base CCS case due to ~17% Capex reduction and ~8% reduction in variable costs. Energy optimization case achieves further reduction of ~3% on the basis of per ton of CO_2 captured. To make this technology commercially viable based on 45Q tax credits, further improvements are needed. Process improvements currently being validated by Svante will increase likelihood of attaining financial viability.

Appendix A. Estimation of Parameters for TEA

Project life and financing assumptions are listed in Table 31.

Table 31. Financing Assumptions for Two TEA Scenarios

	Scenario A	Scenario B
Project life	30	15
Debt	38%	0%
Equity	62%	100%
Real $ cost of debt	5.15%	n/a
Real $ cost of equity	3.10%	7.84%

Finance structure and cost of capital for two scenarios are summarized in Table 32.

Table 32. Real Rates Financial Structure for Two Scenarios

Scenario	Type of security	% of total	Current Dollar Cost (Real)	Weighted average cost of capital (WACC)	After tax Weighted average cost of capital (ATWACC)
A	Debt	38%	5.15%	1.957%	1.453%
	Equity	62%	3.10%	1.922%	1.922%
	Total			3.879%	**3.375%**
B	Debt	0%	2.94%	0	0
	Equity	100%	7.84%	7.84%	7.84%
	Total			7.84%	**7.84%**

LCOCCS = LCC + LOM + LVC + LTS (all expressed in $/T CO_2). Equation 1

Where,

LCOCCS = levelized cost of carbon capture and storage

LCC = levelized capital cost

LOM = levelized O&M costs

LVC = levelized variable costs

LTS = levelized T&S (transportation & storage) costs

LCC:

LCC was calculated per following equations from NETL's QGESS report [2].

LCC = TASC * FCR /(Annual CO_2 volume in T (metric tons))

FCR = CRF/(1 – ETR) – ETR*D/(1 – ETR) Equation 2

CRF = ATWACC*(1 + ATWACC)^y/((1 + ATWACC)^y – 1) Equation 3

$$D = CRF^* \sum_{n=1}^{z} \frac{d_n}{(1+ATWACC)^n}$$ Equation 4

Where,
TASC = total as spent costs

FCR = fixed charge rate

CRF = capital recovery factor

ETR = effective tax rate

ATWACC = after tax weighted average cost of capital

D = present value of tax depreciation expense

d_n = tax depreciation fraction in year n [3]

z = number of years of depreciation (= y +1)

y = number of operating years

Calculations of FCR for two scenarios is summarized in Table 33.

Table 33. Fixed Charged Rate Calculations for Two Scenarios

	Scenario A		Scenario B	
CRF	0.053525		0.115691	
D	0.034186		0.067699	
FCR	0.060228		0.132326	
Year	Depreciation fraction, d_n	$d_n/(1 + ATWACC)^n$	Depreciation fraction, d_n	$d_n/(1 + ATWACC)^n$
1	0.025	0.02418	0.05	0.046365
2	0.04875	0.04562	0.095	0.081689
3	0.04631	0.04192	0.0855	0.068175
4	0.044	0.03853	0.077	0.056934
5	0.0418	0.03541	0.0693	0.047515
6	0.03971	0.03254	0.0623	0.03961
7	0.03772	0.02990	0.059	0.034785
8	0.03584	0.02748	0.059	0.032256
9	0.03404	0.02525	0.0591	0.029962
10	0.03234	0.02320	0.059	0.027737

11	0.03072	0.02132	0.0591	0.025764
12	0.02994	0.02010	0.059	0.02385
13	0.02994	0.01945	0.0591	0.022154
14	0.02994	0.01881	0.059	0.020508
15	0.02994	0.01820	0.0591	0.01905
16	0.02994	0.01760	0.0295	0.008817
17	0.02994	0.01703		
18	0.02994	0.01647		
19	0.02994	0.01593		
20	0.02993	0.01541		
21	0.02994	0.01491		
22	0.02993	0.01442		
23	0.02994	0.01395		
24	0.02993	0.01349		
25	0.02994	0.01306		
26	0.02993	0.01263		
27	0.02994	0.01222		
28	0.02993	0.01182		
29	0.02994	0.01143		
30	0.02993	0.01106		
31	0.01497	0.00535		

TASC:

Calculations for TASC/TOC factors for two scenarios are calculated using following equations from NETL's QGESS cost report [2].

TASC/TOC = Escalation + Cost of funding

Where:

Escalation = $\sum_{n=1}^{y}\left[(1+i)^{(n-1)} * \%capital_n\right]$ Equation 5

Cost of funding = $\sum_{n=1}^{y}\left[WACC * (y-n+1) * (1+i)^{(n-1)} * \%capital_n\right]$ Equation 6

TASC/TOC for Scenario A is in Table 34.

Table 34. TASC/TOC for Three Years for Two Scenarios

Scenario	Cost year	Escalated cost	Cost of funding	WACC	Escalation	Capital expenditure
A	1	0.1	0.011637	0.03879	0%	10%
	2	0.6	0.046548	0.03879	0%	60%
	3	0.3	0.011637	0.03879	0%	30%
	Total	1.0	0.069822			
	TASC/TOC	1.07				
B	1	0.1	0.02352	0.0784	0%	10%

	2	0.6	0.09408	0.0784	0%	60%
	3	0.3	0.02352	0.0784	0%	30%
	Total	1.0	0.14112			
	TASC/TOC	1.14				

LOM:

For real $ basis with zero escalation, levelized O&M costs are same as annual O&M costs, i.e. levelization factor is 1. Annual O&M costs include all the fixed costs such as salaries of personnel, regular maintenance and replacement costs (maintenance material and labor) for plant equipment and operating facilities, taxes and insurance. In NETL's methodology, maintenance material costs are included in the variable costs. The annual O&M costs are assumed to be 3.3% of TOC/year. These costs exclude any consumables such as catalysts, chemicals or solvent, which are included in the variable costs.

LOM = Annual O&M costs/(annual CO_2 volume)

LVC:

The levelized variable costs include costs of all the utilities and consumables such as NG, steam, power, water, chemicals and solvent. In NETL's methodology, fuel cost contribution to levelized cost of product is itemized separate from the other variable costs. Only fuel price was assumed to be levelized fuel price (LFP) from the NETL report. Since steam was assumed to be a fixed multiple of NG cost, it was also priced at levelized cost. For scenario B, NG and steam prices were adjusted to account for change in levelization factor 15 years project life vs. 30 years in Scenario A. This adjustment was estimated by following the methodology for levelized fuel price estimate in the NETL report. Other costs were either taken from the NETL report or from Linde's estimates. These assumptions are listed in Table 35. Consumption of NG, steam, power and water are assumed to be proportional to CO_2 capture volume, while consumption of chemicals are assumed to be fixed annual volumes.

Table 35. Assumptions for Prices of Utilities and Consumables

	Scenario A	Scenario B
LFP for NG, \$/MMBtu HHV	\$4.42	\$4.17
Power, \$/MWh	\$71.7	\$71.7
Water, \$/1000 gal	\$1.90	\$1.90

LVC = (total annual variable costs)/(annual CO_2 capture volume)

LTS:

Levelized transportation & storage costs are assumed to be \$10/T CO_2.

Using approach described above, the LCOCCS was estimated based on captured CO_2 volume as well as based on Scope 1 CO_2 emissions reduced (Scope $1_{non\text{-}CCS}$ – Scope 1_{CCS}).