Final Outcomes Report
Non-Confidential Version

LEHIGH CEMENT EDMONTON CCUS FEASIBILITY PROJECT

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Emissions Reduction Alberta (ERA) contributed $1.4M towards this feasibility study. For 12 years, ERA has been investing the revenues from the carbon price paid by large final emitters to accelerate the development and adoption of innovative clean technology solutions. Since ERA was established in 2009, they have committed $646 million toward 204 projects worth $6.6 billion that are helping to reduce GHGs, create competitive industries and are leading to new business opportunities in Alberta. These projects are estimated to deliver cumulative reductions of 37.7 million tonnes of CO_2 by 2030. For more info: https://eralberta.ca/"

Lehigh Hanson Materials Limited hosts the site of the feasibility study at the Lehigh Cement Plant in Edmonton Alberta. It has been an innovator, partner, and collaborator in advancing the cement and concrete industry and supporting Alberta's economy. Lehigh Cement is a division of Lehigh Hanson Materials Limited (Lehigh Hanson). Lehigh Hanson is a subsidiary of HeidelbergCement AG, one of the world's largest integrated manufacturers of building materials and solutions, with aggregates, cement, and ready mixed concrete businesses around the world. HeidelbergCement is a forerunner on the path to carbon neutrality and has committed to a 30 percent reduction in its CO_2 emissions by 2025 compared to 1990 levels.

International CCS Knowledge Centre (Knowledge Centre) led the completion of the Lehigh Edmonton CCS Feasibility Study, working in partnership with Lehigh Hanson and Emissions Reductions Alberta. The Knowledge Centre's mandate is to advance the global understanding and deployment of large-scale CCS to reduce global GHG emissions. The Knowledge Centre provides the 'know-how' to implement large-scale CCS projects and CCS optimization through the base learnings from both the fully integrated Boundary Dam 3 CCS Facility and the comprehensive second-generation CCS study; the Shand CCS Feasibility Study.

Executive Summary

Lehigh Hanson Materials Limited (Lehigh Hanson) and the International CCS Knowledge Centre (Knowledge Centre) partnered to conduct a feasibility study for the addition of a full scale carbon capture plant at Lehigh's Edmonton Cement Facility. The estimated capacity of the carbon capture plant is up to 780,000 tonnes/yr. Emissions Reduction Alberta (ERA) funded $1.4 million of this $3 million feasibility study.

The Knowledge Centre managed the completion of the feasibility study with support from Mitsubishi Heavy Industries (MHI) Group, Sinoma Energy Conservation Ltd., and Peter Kiewit Sons ULC. MHI is a carbon capture and storage (CCS) technology vendor, specializing in the design of carbon capture and compression equipment. Sinoma Energy Conservation Ltd. is a waste heat capture specialist company that was engaged to examine the potential for waste heat recovery (WHR). Finally, Peter Kiewit Sons ULC, an engineering, procurement, and construction (EPC) company, completed the feasibility study for the balance of plant (BOP) systems required to fully support the implementation of the carbon capture technology at the cement production facility.

The study produced class 4 American Association for the Advancement of Cost Engineering (AACE) capital and operating cost estimates for the addition of a carbon capture and compression plant at the Edmonton Cement Plant. The construction capital cost estimate for the recommended location was $639 million not including escalation, contingency, owner's costs or interest. The annual operating cost was estimated to be $36.5 million.

The feasibility study concluded that amine-based post combustion capture technology can capture 95% of the CO_2 from the combined flue gas flow from the cement plant and the auxiliary steam boiler required for the carbon capture process. The preliminary capture plant design concluded that the captured CO_2 quality would be compatible with either enhanced oil recovery (EOR) or storage in deep geological saline reservoirs.

The utilization of waste heat has the potential to reduce the overall cost of carbon capture projects by reducing the need for additional energy sources, and should generally be evaluated in any carbon capture feasibility study. For this project, the use of excess heat from the preheater tower and the clinker cooling system was studied. It was determined that this heat source can only provide 15% of the required energy and was found to not be cost effective in this application. Thus, 100% of the energy must be supplied by an auxiliary boiler, resulting in a higher overall cost of capture for this application relative to applications suited to high degrees of thermal integration. The additional cost associated with the size of the auxiliary boiler was partially offset by the savings that result from the use of a steam driven compressor.

The carbon capture process requires significant heat rejection which was achieved with a combination of wet and dry cooling. Cooling the flue gas condenses water that is used to supply the wet cooling needs. The waste water from the cooling system can also be used in the existing cement facility process, eliminating the need to dispose of this waste water while reducing the amount of fresh water the plant requires.

The main cement plant site has limited available space to add the carbon capture plant. Two potential locations were studied in detail, and the study recommends installing the capture plant at a location that is not immediately adjacent to the site to minimize construction risks, future maintenance issues, and potential disruptions to plant operations.

Applied knowledge from prior carbon capture projects determined that redundancy, equipment isolation, and flue gas pre-treatment should be included to ensure the capture plant operates reliably and with acceptable degradation of the amine solvent. The results of the detailed stack test were not available to adjust the results of the feasibility study. The level of pre-treatment in the design should be reconsidered based on the stack test results, as there may be capital cost reductions available by implementing dry sorbent injection, ammonia injection or baghouse upgrades within the existing plant boundary.

The feasibility study identified a number of factors that should be examined further during a front-end engineering and design (FEED) study to ensure that the final design is optimized prior to a final investment decision. These factors include: the capture plant size and capture rate, the level of redundancy included in the design, the amount of flue gas pre-treatment (based on stack testing), and the addition of combined heat and power to improve the financial performance of the project.

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List of Abbreviations

AAAQO - Alberta Ambient Air Quality Objectives

AACE - Association for the Advancement of Cost Engineering

ACHE - Air Cooled Heat Exchanger

AEP - Alberta Environment and Parks

AF - Alternate Fuel

AQC - Air Quench Cooler

ASU - air separation unit

BD3 CCS Facility - SaskPower's Boundary Dam Power Station Unit 3 Carbon Capture Facility

BOP - Balance of Plant

CAPEX - Capital Expenditure

CCIR - Carbon Competitiveness Incentive Regulation

CCS - Carbon Capture and Storage

CCUS - Carbon Capture, Utilisation and Storage

CCW - closed cooling water

CHP - combined heat and power

CIB – Canadian Investment Bank

CIP - Clean in Place

CPM - Condensable Particulate Matter

DC - Direct Control

EDG - Emergency Diesel Generator

EIA - Envrionmental Impact Assessment

EIP - Energy Innovation Program

EOR - Enhanced Oil Recovery

EPC - Engineer, Procure and Construct

EPCOR - EPCOR Distribution and Transmission Inc.

EPEA - Environmental Protection and Environment Act

ERA - Emissions Reduction Alberta

ESA - Environmental Site Assesment

FEED - Front End Engineering and Design

FGD - Flue Gas Desulfurization

FPM - Filterable Particulate Matter

FRP - Fiberglass Reinforced Polymer

GHG - Greenhouse Gas

HMI - Human Machine Interface

HP - High Pressure

ITC – Investment Tax Credit

LP - Low Pressure

MCCs - Motor Control Centers

MHI - Mitsubishi Heavy Industries

MP - Medium Pressure

NG - Natural Gas

PCS - Process Control System

PFD - Process Flow Diagrams

PFDs - Process Flow Diagrams

PFHE - Plate and Frame Heat Exchanger

RO - Reverse Osmosis

SIF - Strategic Innovation Fund

SP - Suspend Preheater

SWMF – Stormwater Management Facility

TDS - Total Dissolved Solids

TEG - Triethylene Glycol

TIER - Technology Innovation and Emissions Reduction

US - United States

VFD - Variable Frequency Drive

VOC - Volatile Organic Compound

WAA - Water Act

WESP - Wet Electrostatic Precipitator

WHR - Waste Heat Recovery

WHRU - Waste Heat Recovery Unit

WSAC - Wet Surface Air Cooler

HHV – High Heating Value

Nomenclature

CO_2 - Carbon Dioxide

H_2O - Water

H_2SO_4 - Sulfuric Acid

HCl - Hydrochloric Acid

Na - Sodium

NH_3 - Ammonia

NO_2 - Nitrogen Oxides

NO_X - Nitrogen Oxides

SO_2 - Sulfur Dioxide

SO_3 - Sulfur Trioxide

SO_4 - Sulfate

SO_X - Sulfur Oxides

Units

$ - Canadian Dollar

%mol - Perecnt by Mole

%vol - Percent by Volume

°C - Degrees Celsius

bar - Bar

bar abs - Bar Absolute

g - Gram

h - Hour

kmol - Kilomole

kPa - Kilopascal

kV - Kilovolt

kW - Kilowatt

m - Meter

M - Million

m^3 - Cubic Meter

mg - Milligram

mm - Millimeter

mt - Metric Ton

Nm^3 - Normal Cubic Meter

ppm - Part Per Million

s - Second

Chapter 1 Project Description

1.1 Project Background

The Lehigh Hanson Materials Limited Edmonton Cement Plant (Lehigh Edmonton) carbon capture and storage (CCS) feasibility study, jointly conducted by Lehigh Hanson Materials Limited (Lehigh) and the International CCS Knowledge Centre (the Knowledge Centre), evaluated retrofitting a cement production facility at Lehigh (Edmonton, Alberta, Canada) with a full-scale, post combustion, amine-based Carbon Dioxide (CO_2) capture system. This study delivered an Association for the Advancement of Cost Engineering (AACE) Class 4 cost estimate to assist Lehigh in determining the economic viability of a potential CCS retrofit project. This feasibility study commenced in November 2019, and was completed in the fall of 2021, with a budget of $3.0 million CAD. Funding for this study has been provided by Lehigh and Emissions Reduction Alberta (ERA) with contributions by the Knowledge Centre.

In delivering this study, the Knowledge Centre engaged with Mitsubishi Heavy Industries (MHI) Group, Kiewit Corporation, and Sinoma Heat Energy Conservation Ltd., for the design of the CO_2 capture system, balance of plant study, and the evaluation of waste heat recovery, respectively.

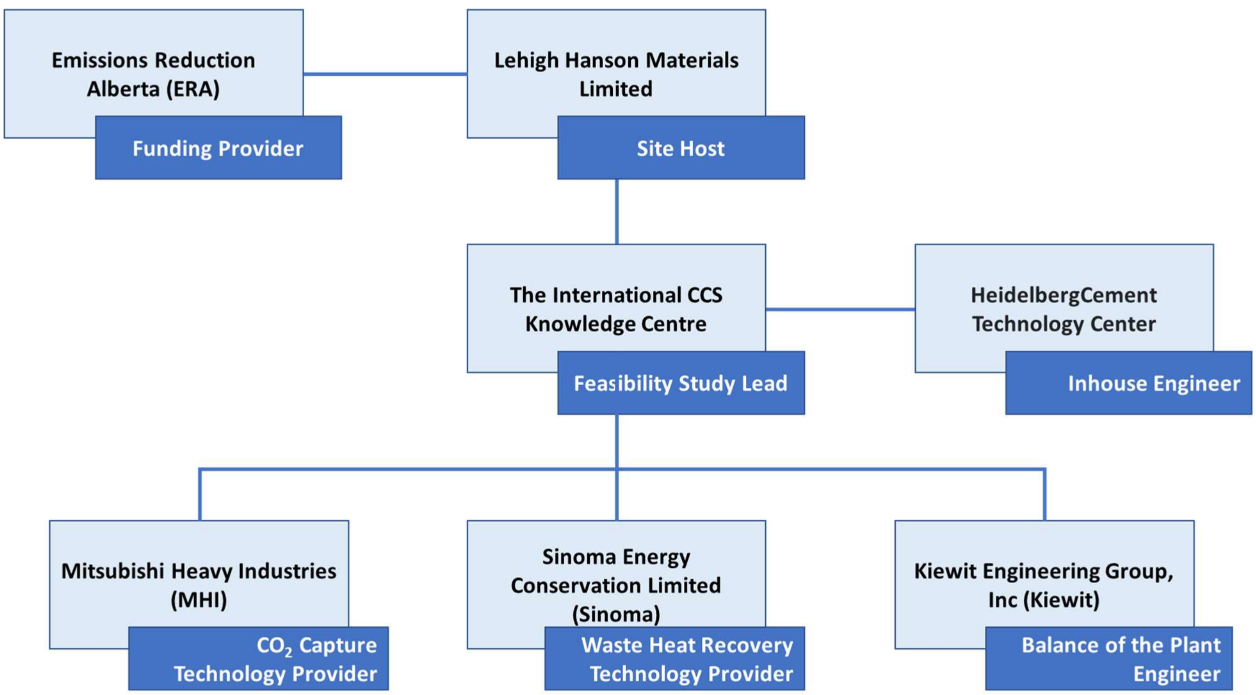


FIGURE 1.1 PROJECT ORGANIZATION CHART

The direction and guidance from the Knowledge Centre utilized base learnings from both the Boundary Dam 3 CCS Facility and the second-generation CCS study; the Shand CCS Feasibility Study.

1.2 An Overview of Lehigh Cement Edmonton

1.2.1 Lehigh Edmonton

Lehigh Cement is a division of Lehigh Hanson Materials Limited (Lehigh Hanson). Lehigh Hanson is a subsidiary of HeidelbergCement AG, one of the world's largest integrated manufacturers of building materials and solutions, with aggregates, cement, and ready mixed concrete businesses around the world. Lehigh Cement operates a portland cement manufacturing plant at 12640 Inland Way in Edmonton, Alberta

FIGURE 1.2 LEHIGH CEMENT PLANT

1.2.2 Lehigh Cement Edmonton Plant's Current Operation

Lehigh Cement's Edmonton plant produces approximately 800,000 - 1,000,000 tonnes of cement per year depending on market demand. The process begins with limestone, the main raw material, which is delivered to the site by rail. The limestone is combined with clay and other raw materials then crushed and blended into a powdered mixture which is sent to a preheater and then to a rotary kiln. In the rotary kiln, the powdered mixture is heated to temperatures as high as 1,400 degrees Celsius (°C). At these temperatures, the raw mineral inputs recombine to form nodules of cementitious crystals called clinker. The clinker exiting the kiln is cooled by ambient air in a grate cooler prior to storage. Clinker is subsequently ground into a fine powder with gypsum, limestone, and supplementary cementing materials to form portland cement, which is later combined with sand, gravel, and water to produce concrete. Concrete used for construction typically contains between 10 and 15% portland cement. Concrete is the world's second-most used building material, behind water.

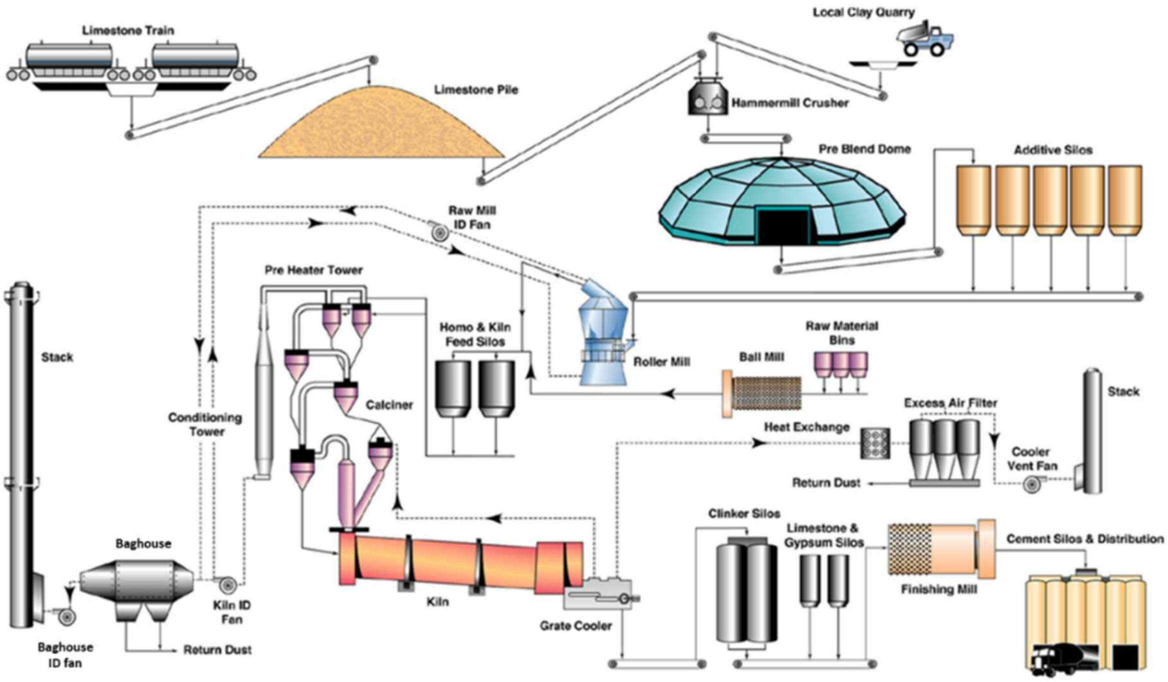


FIGURE 1.3PROCESS FLOW DIAGRAM OF CEMENT PRODUCTION AT LEHIGH

The Edmonton kiln system can be operated with a variety of fuels. The decision of which fuel to use is based on cost, availability, and impact on the overall emissions of the plant. Possible fuels for this plant include:

- 100% natural gas (NG)
- 100% coal
- 50% NG /50% alternate fuel (AF)

Alternative fuels are normally derived from industrial, commercial, institutional and construction byproducts, household residential byproducts, and/or biomass. For this study, the assumed fuel source was 100% natural gas.

1.3 Drivers for CCS Implementation

Canada is known as a pioneer in CCS technology with four large-scale capture facilities operating to date. Early-mover projects like Shell Quest (Alberta) and Boundary Dam (Saskatchewan) CCS projects not only assumed the risks and costs associated with the learning curve experienced by first-mover projects, but they are also contributing valuable global leadership based on the experience gained and lessons learned developing, delivering, and operating their facilities.

With a renewed momentum and drive for emission reductions nationally and globally, Alberta is looking to position itself as a world leader in CCS in the very near future. As the backbone of the province's economy, Alberta relies on revenues from large industries. With 70% of emissions coming from these sectors, Alberta's economic identity is tied to the province's large emissions profile.[1] As such, Alberta is

[1] Environment and Climate Change Canada. National Inventory Report

primed to take action and is doing so with a sense of urgency as it leans on Canada's expertise in CCS. In the spring, Alberta underscored its commitment to Canada's ambitious 2030 and 2050 targets by publicly announcing it would substantially reduce the province's major sources of industrial emissions with large-scale CCS. The goal is to double its already ongoing emissions reduction contribution of 30Mt to 60Mt or more with a pitch for a $30 billion investment from the Canadian federal government.[2] This money will likely be made available through funding programs such as the Strategic Investment Fund (SIF), Canadian Investment Bank (CIB), and/or the Investment Tax Credit (ITC) and be accessible to all provinces. Contributions from the province of Alberta are also expected. The depth of experience in the application of CCS in Alberta expands beyond the companies that build and operate facilities to include the established best practices and guidelines that are necessary for safe operations.

The landscape for CCS projects is changing, both within the province of Alberta and Canada. Alberta has put in place policy and regulatory frameworks that safeguard the public interest, as well as environmental sustainability. This includes well-established regulations and practices for measuring, monitoring and verification, rules for long-term liability, pore space management, and the establishment of a carbon capture fund with required knowledge sharing criteria. These factors create an enabling environment.

The Lehigh Edmonton facility emits up to 780,000 tonnes of CO_2 annually, with approximately two-thirds of those emissions produced via the calcination process, and approximately one-third arising from combustion. In a conventional cement plant, CO_2 from combustion and calcination are produced concurrently in the cement kiln system and the two streams of CO_2 are combined in the kiln's exhaust gas.

As the world moves towards decarbonizing more industrial sectors, the cement industry is making progress towards reducing emissions from combustion through fuel switching and energy efficiency improvements, but the emissions from the calcination of limestone are effectively irreducible. CCS offers the opportunity to mitigate the CO_2 emissions from both combustion and calcination processes.

1.4 Technology Selection

To date, there have been no large-scale commercial CO_2 capture projects implemented in the cement sector. In principle, a range of CCS technologies are applicable to cement plants. In this study, the following options were evaluated:

- Amine absorption,
- Oxyfuel combustion,
- Chilled ammonia,
- Membrane-assisted CO_2 liquefaction, and,
- Calcium looping.

A comparison of the available CO_2 capture technologies is presented in Table 1.2. Owing to its technology readiness level of 9, amine absorption has been identified as the only viable candidate for large-scale commercial deployment in the near term. This technology has been applied in two coal fired power stations, SaskPower's Boundary Dam Power Station Unit 3 Carbon Capture Facility (BD3 CCS Facility) in Saskatchewan, Canada, and the Petra Nova Project at the W. A. Parish Power Station in Texas, United

[2] CBC (March 2021) Alberta asks federal government to commit $30B to advance carbon capture technologies

States (US). Owing to similarities in the composition of the flue gas to be treated, many of the learnings associated with the Boundary Dam and Petra Nova facilities can be transferred to the Lehigh facility.

TABLE 1.1 TECHNOLOGY COMPARISON

Criteria	Amine Absorption	Oxyfuel	Chilled Ammonia	Membrane-Assisted CO_2 Liquefaction	Calcium Looping
Requires modifications to the existing cement process	no	yes	no	no	minor for tail pipe implementation,
Development status	commercially available in different industry sectors, pilot scale testing on cement	requires R&D	requires R&D	requires R&D	experience in small scale, requires R&D
Technology Readiness Level[3]	9	5[4]	6-7	7	7
level of required cement plant modifications	retrofitting possible - no kiln redesign is required. steam cycle needed	ASU/CPU required. Modifications at the kiln plant required, existing plant structure has to allow the integration of oxyfuel infrastructure	retrofitting possible - no kiln redesign is required	Refrigeration system needed	ASU and steam cycle needed
Effect on cement kiln operation	minimal impact on existing cement kiln process	process and material reaction is influenced	minimal impact on existing cement kiln process	minimal impact on existing cement kiln process	process and material reaction is influenced
CO_2 purity	high CO_2 purity is possible (>99 vol. %)	high CO_2 purity (>99% vol) is possible	high CO_2 purity (>99% vol) is possible	high CO_2 purity (>99% vol) is possible	high CO_2 purity (>99% vol) is possible
Applicability to existing plants	retrofitting is possible and no kiln redesign is required, high space requirement for capture plant	retrofitting is feasible with modification at the kiln plant, space requirement for ASU/CPU	requires R&D: pilot scale only	requires R&D: pilot scale only	requires R&D: pilot scale only
Energy demand	intensive to regenerate solvent	intensive to operate air separation unit	Intensive to refrigeration system	Intensive to pressurize gases	intensive to regenerate sorbent
Acid Gas control (SO_2, HCl)	required	may be required	required	required	may be required

[3] Global CCS Institute, (2021) Technology Readiness and Costs of CCS, www.globalccsinstitute.com/wp-content/uploads/2021/04/CCS-Tech-and-Costs.pdf
[4] TNO, (2020) Oxyfuel Combustion CO_2 Capture - Gaseous Fuels, www.energy.nl/wp-content/uploads/2020/09/CCS-Oxyfuel-Combustion-Power-Gaseous-fuel.pdf

1.5 Project Objectives

To support Canadian policies on climate change protection, Lehigh Cement is leading the development of a large-scale CCS project at its Edmonton plant. The Lehigh Edmonton CCS Feasibility study was the first step of investigation for CCS deployment. This feasibility study had the following objectives:

- Produce an AACE Class 4 capital and operating cost estimates for the addition of a carbon capture facility including the required BOP systems,
- investigate the effects of cement plant flue gas composition on the CO_2 capture process and identify mitigation strategies,
- investigate the potential of heat recovery from the existing cement plant to fulfill the energy requirement of the CO_2 capture process,
- implement a heat rejection system,
- propose a water management strategy, and
- obtain knowledge on deployment of CO_2 capture and compression process on cement production facilities which can be shared with other cement facilities around the world.

Table 1.2 shows the project success metrics indicated in the contribution agreement between ERA and Lehigh. The success metrics and targets are discussed in detail in Chapter 13.

TABLE 1.2 PROJECT SUCCESS METRICS

Success Metric	Target
Capture efficiency	Plant designed to capture min 95% of CO_2 in exhaust gas.
CO_2 capture plant capacity	Plant designed to handle anticipated CO_2 input per day.
Waste Heat Recovery-cost	Cost to build and operate waste heat recovery system is less than or equal to cost to build and operate gas fired boiler.
BOP systems – layout	Capture plant will fit in available space.
BOP systems – heat rejection	Sufficient cooling resources available to reject heat from regeneration process.
CO_2 product quality	CO_2 quality acceptable for beneficial re use such as EOR.
Feasibility study – capital and operational cost estimate	Project costs identified to class 4.

1.6 Design Criteria

1.6.1 Capture Plant Size

The CO_2 capture plant at the Lehigh facility was designed to capture CO_2 from three different sources; process CO_2 generated by the calcination of limestone, combustion CO_2 emitted from the fuels used for clinker production, and the combustion CO_2 emitted from a natural gas fired auxiliary boiler required for the CO_2 capture and compression process.

The plant size was selected by reviewing current and expected clinker production and a range of future fuel mixes provided by Lehigh. This capacity was chosen to accommodate peak production rates and auxiliary boiler emissions under most operating scenarios.

As part of the system design process, the auxiliary boiler size was increased to allow the use of a steam driven compressor instead of an electric motor driven compressor. It was decided not to increase the capacity of the capture plant further to accommodate this additional CO_2 because the additional auxiliary boiler emissions could be accommodated under average production circumstances. However, under peak production and peak flue gas flow operating conditions a portion of the auxiliary boiler emissions would be vented, bypassing the capture process. Selection of the capture plant capacity has significant implications as it cannot be increased in the future, and some design margins are warranted. The size of the capture plant will be further refined and optimized during the FEED study.

1.6.2 Site Conditions

Table 1.3 shows the design conditions used for the Lehigh Edmonton CCS Feasibility Study.

TABLE 1.3 DESIGN SITE CONDITIONS AT LEHIGH EDMONTON

Items	Unit	
Site location		12640 Inland Way NW, Edmonton, Alberta, Canada
Site elevation	m	671
Average atmospheric pressure	kPa	93.5
Average ambient temperature	˚C	3
Design wet bulb temperature (85th percentile)	˚C	12.5
Design dry bulb temperature (85th percentile)	˚C	16.5
Minimum ambient process design temperature	˚C	-45
Maximum ambient process design temperature	˚C	35
Minimum temperature in hottest month	˚C	12.3
Average relative humidity	%	71.6
Average annual precipitation	mm	456
Average wind speed	km/h	13.4
Maximum wind speed	km/h	117
Dominant wind direction		W

1.6.3 Flue Gas Composition

Currently, hot flue gases from the clinker process are cooled in the conditioning tower before entering the main baghouse. The flue gas temperature at the main bag-house inlet is controlled by a direct contact water spray system in the conditioning tower to protect the bags from high temperature flue gas. The dust particles in the kiln flue gases are filtered at the main baghouse before the filtered flue gas is released to the atmosphere through the kiln stack.

Table 1.4 shows the parameters and compositions of the flue gas exiting the kiln stack which were used in the design of the carbon capture system. The volume and constituent specifications for the flue gas were derived from historical plant operating and stack testing data. Various scenarios, reflecting a range of operating conditions that could be expected given a range of production levels, fuel mixes, moisture, and false air contribution, were reviewed to determine representative design and operating conditions for this study.

The flue gas design values considered the maximums for volumetric flow and contaminant concentrations in the database while the CO_2 mass flow was a function of historical best 30-day production and future fuel mixes. The operating values were derived from the average flue gas conditions when firing 100% natural gas as a fuel (the normal operating condition in 2019).

Table 1.4 Flue Gas Composition at Lehigh Kiln Stack

Items	Unit	Design	Operating
Temperature	°C	210	120
Pressure	bar	0.94	0.94
Molecular Weight	kg/kmol	28.71	28.71
Mass Density	kg/m^3	0.83	0.83
Molar Flow	kmol/h	20,353	17,721
Mass Flow	kg/s	162.29	141.31
Volumetric Flow	m^3/h	707,500	616,000
Composition			
H_2O	mole %	17	17
CO_2	mole %	12.36	12.36
O_2	mole %	10.38	10.38
N_2 + Ar	mole %	60.26	60.26
Composition			
NO	ppm	309	309
NO_2	ppm	10.72	10.72
SO_X	ppm	6.29	4.32
NO_X	ppm	320	320
Filterable Particulate Matter (FPM)	mg/Nm^3 dry	6.4	17.1

1.6.4 Other Design Considerations

1.6.4.1 Weather Condition

In Edmonton, the normal ambient temperature ranges from +35°C to -45°C seasonally. This weather variation needs to be taken into consideration for designing the CO_2 capture plant and BOP systems. For this project, compact buildings are proposed to save cost, however additional space is required for maintenance indoors during winter. The consideration on which equipment is installed indoors and outdoors was based on the required level of maintenance. Equipment which requires frequent maintenance will be installed inside of a heated building with enough access for maintenance and equipment requiring less maintenance will be installed outside. Owing to the cold weather in Edmonton, the equipment installed outdoors will need to be heat traced or provisions made to keep flows circulating.

1.6.4.2 Heat Integration and Waste Heat Recovery

The cement facility has various sources of waste heat that may provide useful energy. After a preliminary review of the Lehigh facility, two sources were identified as having the potential to provide useful energy for the carbon capture process, the kiln flue gas stream and the clinker cooler flue gas. Both waste heat sources are available when the kiln is operating. However, this study revealed that waste heat recovery was not economically viable in this instance.

1.6.4.3 Heat Rejection Design and Water Management

The heat rejection system was designed to utilize water discharged from the capture plant to minimize the impact of water balance on the existing Lehigh plant. The heat rejection system consists of dry and wet cooling connected in series. The wet cooling section will consume the water discharged from the capture plant and the remaining heat rejection load will be handled in the dry cooling section.

Owing to local conditions in Edmonton, the selection of the design temperature for the cooling system is challenging. The heat rejection system for the capture plant was designed for the 85th percentile to reduce the capital cost. When the ambient temperature is higher than the design point, the capture plant can be operated at the design capture rate, but it will require higher energy inputs and solvent consumption rates.

1.6.4.4 Site Layout Considerations

The site layout was one of the biggest challenges in this feasibility study as the existing cement plant is congested and is located in an urban setting. The selection of the capture plant and BOP system location considered the space available and the constructability of the new facilities, while minimizing the impact on operations. A desktop siting study was performed to evaluate site locations and arrangements for the CO_2 capture plant and the BOP systems.

1.6.4.5 Redundancy and Isolation

In this feasibility study, redundancy and isolation were applied to selected areas of the CO_2 capture plant and BOP systems based on the BD3 CCS facility design and operating experience. Redundancy was added to equipment that is vital in achieving continuous process operations or equipment susceptible to frequent fouling. Isolation was also included to allow online maintenance or cleaning of fouled equipment. The addition of redundancy and isolation increases the capital cost in order to minimize shutdowns of the carbon capture plant and reduce future maintenance costs.

1.6.4.6 Plume Visibility

The cement plant is located in a major urban center, which requires that particular attention be paid to plume visibility. The emissions from the capture plant including the absorber and heat rejection system will be within regulatory emissions limits, however, a visible water vapor plume is often associated by the public with perceived poor environmental performance. In addition, there is potential for the moisture to produce ground level fog that could affect visibility on major roadways as well as the capture plant itself. To mitigate the plume visibility from the heat rejection system, the wet surface air cooler (WSAC) will be designed with a plume abatement system. For the absorber tower plume, potential design adjustments to minimize plume visibility will be studied in detail during the FEED study.

Chapter 2 Desktop Siting Study

The purpose of the desktop siting study was to evaluate site locations and arrangements for the CO_2 capture plant and BOP systems. An order of magnitude cost evaluation was performed to compare the siting options.

2.1 Lehigh Property Boundaries and Access

2.1.1 Site

The Lehigh Cement Plant occupies a site that is approximately 26 hectares (64 acres) in size. It is bordered on the east and south by Canadian National Railroad tracks, and on the north and west by a closed municipal waste landfill owned by Waste Management. The plant is located in an industrial area approximately 8 kilometers northwest of downtown Edmonton, near the intersection of 170th Street NW and the Yellowhead Trail (Highway 16). Figure 2.1 shows an aerial view of the plant and its surroundings.

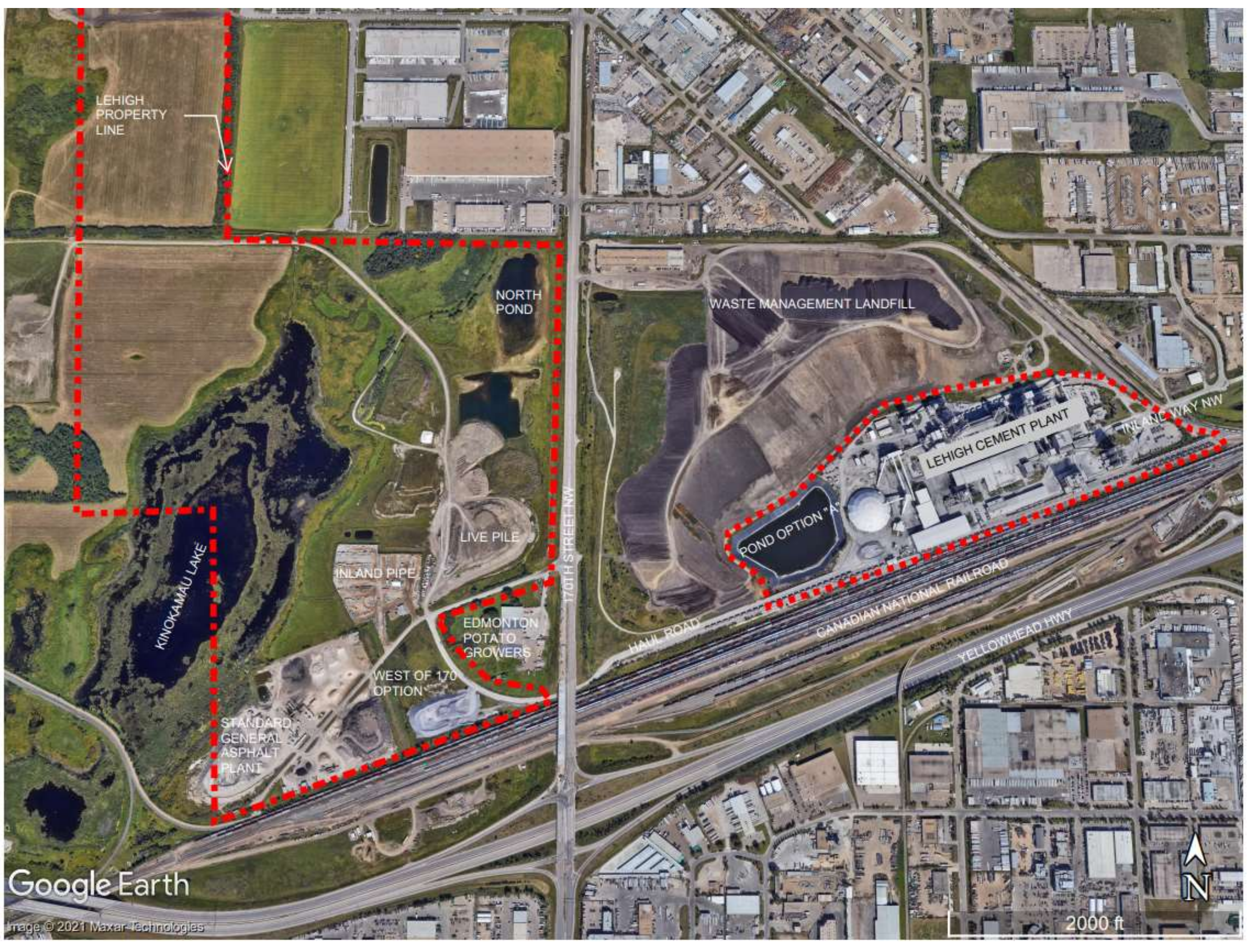


FIGURE 2.1 LEHIGH CEMENT PLANT AND SURROUNDINGS

2.1.2 Process Water Pond

A process water pond is located at the west end of the plant. In addition to providing process and cooling water to the plant, the pond also serves as a stormwater retention basin for the plant and landfill. Storm runoff received by the pond is retained for use by the plant and is not discharged offsite.

The water level in the pond is regulated in a tight elevation range to prevent flooding in the plant. Lehigh manages the pond volumes seasonally and will supplement the pond volumes using deep well pumps located on site. During emergency or flooding conditions, water is discharged to adjacent water bodies through permitted processes or if authorized could be discharged to the City of Edmonton.

2.1.3 Road Access

The plant is accessed from the east by a city street named Inland Way NW, and from the west by an unnamed haul road that connects to the southbound lanes of 170th Street NW. The haul road crosses under the 170th Street bridge that spans the Canadian National Railway tracks, and then runs in a dedicated easement across the landfill parcel to reach the plant. Bulk raw material carriers and normal plant traffic use the Inland Way entrance. Limestone is delivered by rail and other raw materials (clay, iron, sand, and bottom ash) are delivered by trucks using the haul road.

2.1.4 Area West of 170th Street

Lehigh owns approximately 136 hectares (336 acres) on the west side of 170th Street, as indicated in Figure 2.1. Standard General leases some of this is for an asphalt batch plant operation, and Inland Pipe occupies a tract that it uses for a pipe and manhole storage yard. Lehigh utilizes a portion of the property for its live clay pile and other material stockpiles.

2.2 Carbon Capture Site Options and Early Investigations

Four potential sites plus two configurations for one site were investigated for the CO_2 capture plant and BOP system installations. These options including:

(1) Pond Option A,
(2) Pond Option B,
(3) West of 170,
(4) East Parking Lot, and
(5) South of Kiln.

Figure 2.2 (A) and Figure 2.2 (B) shows the location of the five options. The evaluation considered available space for the permanent plant, cranes and module staging, and cold and heated storage. It also considered issues such as the use of modular construction, access via Alberta Highway and Edmonton public streets, local workforce access, project constructability, and potential risks to continuity of Plant operations. The impacts to local rail, cement truck traffic (100 trucks per day), alternate fuel traffic (20-40 trucks per day), clay, sand, and bottom ash materials (50 trucks per day) and other risks and constraints that may be identified in the preliminary stages were also considered. A summary of each option, including their advantages, disadvantages, and risks, appears in the following sections.

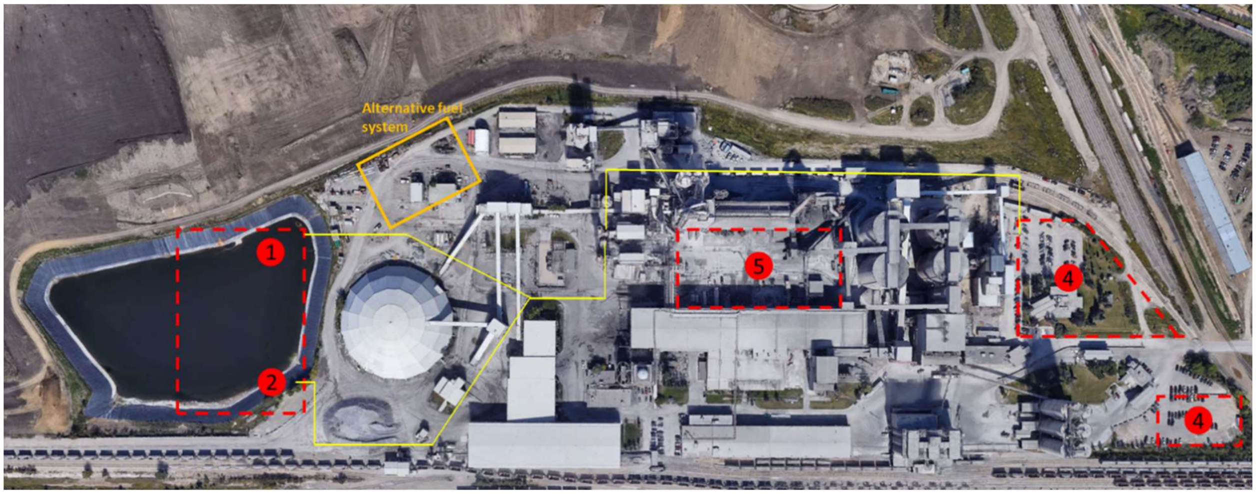


FIGURE 2.2 CO_2 CAPTURE PLANT AND BOP SYSTEM POTENTIAL SITE LOCATION (A)
(1) Pond Option A (2) Pond Option B (4) East Parking Lot (5) South of Kiln

FIGURE 2.2 CO_2 CAPTURE PLANT AND BOP SYSTEM POTENTIAL SITE LOCATION (B)
(3) West of 170

2.2.1 Pond Option A and B

The two pond options include locating the capture plant and BOP systems in place of the existing pond. These options require at least partial relocation of the existing pond, which provides for storm water management and process cooling needs. The difference between these two options is the orientation of the capture plant and location of the flue gas tie-in to the capture plant. For pond option A, the flue gas duct tie-in is at the north side of the capture equipment while for pond option B the tie-in is at the south side. Table 2.1 shows the advantages and disadvantages identified for the two pond options.

TABLE 2.1 THE ADVANTAGES AND DISADVANTAGES IDENTIFIED FOR THE POND OPTIONS

Advantages	• Lower impact to existing operations during construction than some of the other options. • BOP equipment in close proximity to carbon capture equipment results in lower quantities for BOP piping, steel, raceway, etc. • Construction traffic from the west minimizes impact to operations. • pond option A has a shorter flue gas duct route than pond option B. • Electrical interconnection is close to existing transmission line assuming that a new transmission line can parallel the route of the existing line.
Disadvantages and Risks	• Pond relocation is required. Two potential pond locations to be evaluated, both on the west side of 170th Street. • Flue gas duct crosses multiple conveyors. Alternate duct route around the north side was evaluated. • Routing of piping along haul road and at 170th Street road crossing (rights-of-way and land ownership considerations). This piping is required for connecting the relocated pond to the existing storm water drainage and process infrastructure. • The site footprint is crowded. • There will be significant coordination required with the cranes. • There is little room for additional equipment beyond what is currently envisioned. The addition of a cogeneration unit to supply the heat to the unit will be difficult, and other required items that may be discovered during the FEED study will be constrained for footprint. • A dual loop hybrid cooling configuration is not feasible for the pond option • A complicated construction sequence is required to move the pond. • The level 1 schedule shows that the pond relocation impacts critical path by 5 months, requiring either an early commitment of relocation funds or delaying the project.

Two potential locations have been identified for the relocated pond as shown in Figure 2.3 Relocated Pond Options. The evaluation of the pond location options was based on environmental, permitting, and easement perspectives.

- Pond relocation option 1 is closer to the plant and existing pond which would result in lower piping quantities between the new plant and pond.
- Pond relocation option 2 is further from the plant and existing pond which would results in greater piping quantities between the new plant and pond. Pond option 2 was ultimately selected as it has less impact on potential future uses of the land.

FIGURE 2.3 RELOCATED POND OPTIONS

2.2.2 West of 170 Option

The west of 170 option includes locating the capture plant and BOP systems on the west side of 170th Street. This results in a long flue gas duct but has the advantage of the being less disruptive to existing operations during construction.

TABLE 2.2 THE ADVANTAGES AND DISADVANTAGES IDENTIFIED FOR WEST OF 170 OPTION

Advantages	• Least disruptive to existing Plant operation during construction. • BOP equipment in close proximity to carbon capture equipment. • Available laydown space near construction area. • Existing pond not impacted. • Supports alternative plant ownership models. • Construction efficiencies due to laydown being closer to the working area, contractor parking/equipment laydown area/labour overall efficiency/access efficiency (vs winter weather work/contractor trailer location for pond option). • A dual loop hybrid cooling configuration is feasible for the west of 170 option • This option keeps the door open for the future addition of combined heat and power.

Disadvantages and Risks	• Longest flue gas duct (higher capital and operating costs). • Feasibility of flue gas duct road crossing at 170th Street. • Permission and permitting for flue gas duct with local authorities (City of Edmonton). • Routing of duct and piping along haul road (rights-of-way and land ownership). • Utilities considerations (gas, potable water, service water, fire water, sanitary sewer). Further away from existing utility connections at plant. • Plant operating staffing and management – distance between carbon capture plant and cement plant (two distinct sites physically separated may require some considerations on operations). • Long steam and condensate return for waste heat recovery units (WHRUs). • Transmission line and interconnection point are not confirmed.

The major challenge with this option is crossing 170th Street with the large flue gas duct. The flue gas duct design challenges are described in more detail in Chapter 3.

2.2.3 East Parking Lot Option

The east parking lot option locates the capture plant where the current employee parking and office building are located. The BOP equipment is located over another parking lot at the southeast corner of the Plant.

TABLE 2.3 THE ADVANTAGES AND DISADVANTAGES IDENTIFIED FOR EAST PARKING LOT OPTION

Advantages	• Existing pond is not impacted. • BOP equipment in close proximity to the capture plant.
Disadvantages and Risks	• Requires demolition and relocation of the Plant office building. • Loss of parking for Plant personnel and contractors. • Constrained space for construction. • Farthest from available laydown area (land west of 170th Street). • Impact to existing operations (product loading vehicle traffic). • Long and difficult flue gas route due to rail, silo, conveyor, and power line crossings.

2.2.4 South of Kiln Option

The south of kiln option locates the capture plant and some of the BOP equipment south of the kiln and in the area of the storage hall.

TABLE 2.4 THE ADVANTAGES AND DISADVANTAGES IDENTIFIED FOR SOUTH OF KILN OPTION

Advantages	• Existing pond is not impacted. • Shortest flue gas duct.
Disadvantages and Risks	• BOP farther from carbon capture which increases quantities, design, and construction complexity. • Requires demolition of part of the storage hall and rework of existing utilities. Increases potential for exposure to asbestos, polychlorinated byphenyls (PCB's), and other potential hazards. • Highest risk and potential impact to plant operations and damage to existing equipment during construction. • Loss of contractor parking. Relocation of parking is required. • Far from laydown area (land west of 170th Street). • Substation is far from the capture plant.

2.3 Cost Evaluations and Recommendations

The goal of the desktop siting study was to select two options for further development of conceptual design and Class 4 cost estimate. The five potential options for the proposed CO_2 capture plant and BOP systems were evaluated based on advantages, disadvantages, risks, and cost premiums. A rough order of magnitude (ROM) cost evaluation was performed to evaluate differential costs for major items including:

- Kiln and auxiliary flue gas ducts and supports to the capture plant,
- Pond relocation, earthwork, liner, pump house, piping, cooling tower
- Buildings – demolition and new construction
- Separation of carbon capture and BOP equipment
- Electrical interconnects
- Power delivery
- Construction

The preliminary cost evaluation indicated that the east parking lot option and south of kiln option have the highest evaluated premium cost, driven primarily by construction difficulty and building relocations. The pond option A was the lowest evaluated cost alternative at this stage with a slight edge over pond option B due to having the shorter flue gas duct route.

The options that were determined to be the most viable for further study were pond option A and west of 170th Street. in Chapter 11, the cost comparisons for these two options are summarized and discussed. Note, from this point forward in the report the options designations were simplified and are referred to as the pond option and the west of 170 option.

Chapter 3 Flue Gas Supply

Flue gas ducts are required to carry flue gas from the existing kiln flue gas system and from the new auxiliary boiler to the inlet of the CO_2 capture plant. Design and costing of the flue gas supply system were completed for the pond option and west of 170, options.

The impact on cost of duct size, pressure drop along the duct, and shape (round or square) were evaluated for each location. Duct support design and flue gas control concepts are also described. The proposed methods for the flue gas duct crossing of 170th Street are presented in this chapter.

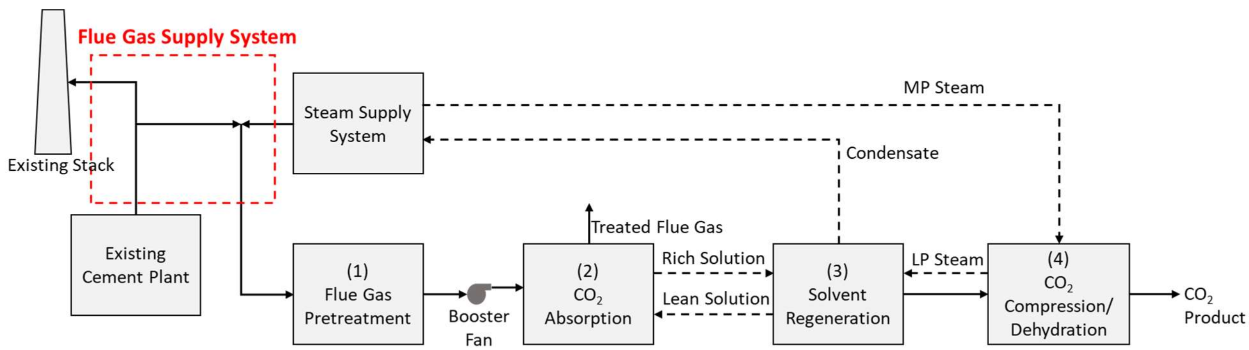


FIGURE 3.1 FLUE GAS SUPPLY SYSTEM

3.1 System Description

The flow diagram of flue gas supply system is illustrated in Figure 3.2. Flue gas from the kiln baghouse ID fan outlet duct is directed to the CO_2 capture plant through new ductwork. The tie-in to the existing duct is near the existing main stack. Two louver dampers are used to send the flue gas to either the existing stack or the CO_2 capture plant. A guillotine gate provides isolation of the flue gas duct downstream of the diverter damper, this gate provided isolation of the capture plant from the kiln to allow capture plant maintenance with the kiln in operation. The flue gas from the auxiliary boiler is added to the kiln flue gas with the combined gas directed in a relatively short duct to the flue gas quencher of the CO_2 capture plant. The auxiliary boiler also has a bypass stack that can be used when the auxiliary boiler is operating but the gas cannot be sent to the CO2 capture plant (e.g., on startup).

There is a backpressure damper downstream of the auxiliary boiler's diverter damper. Its purpose is to provide backpressure to the boiler because of the negative pressure in the main duct to the CO_2 capture plant, so that the pressure at the base of the existing stack can be near atmospheric. During the next phase of this project, an evaluation may determine that this damper is not needed. This is because the auxiliary boiler FD fan controls (e.g., flow control damper) may be able to accommodate the negative pressure in the main duct.

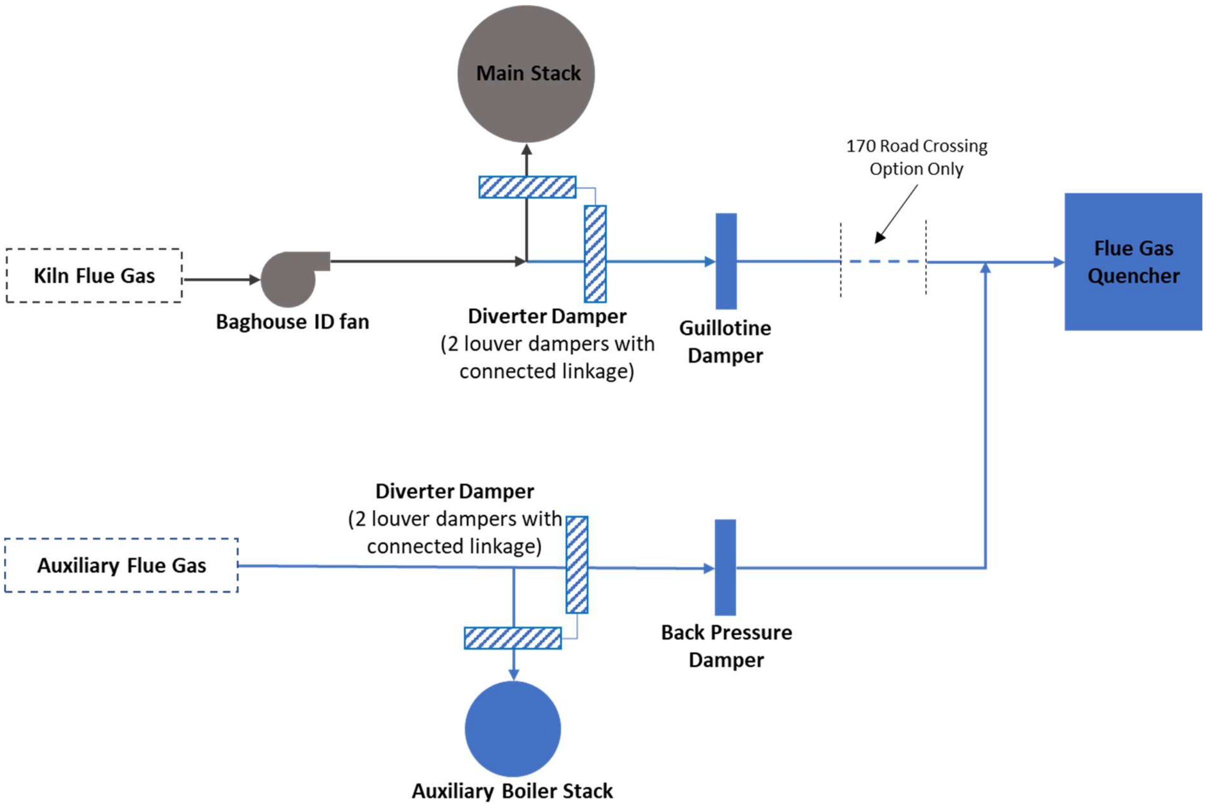


FIGURE 3.2 FLOW DIAGRAM OF FLUE GAS SUPPLY SYSTEM

3.2 Duct Selection and Sizing

3.2.1 Duct Materials

The duct material selection is based on the flue gas conditions. The key parameters are temperature and sulfur trioxide (SO_3) concentration. SO_3 in flue gas combines with the water vapor in the flue gas to form sulfuric acid (H_2SO_4). The flue gas from the kiln is at 120 °C. The sulfuric acid dewpoint of this flue gas (with 3.2 ppmv of SO_3) is 131 °C. Therefore, condensation of sulfuric acid is likely on the duct surfaces. Drains in the duct spaced out over the duct length may be required to collect this condensation. If required, the drains will be routed to tanks or sumps and pumped to a wastewater treatment system. Based on the potential for sulfuric acid condensation, two possible duct materials are coated carbon steel or Alloy 2205, a duplex stainless steel. Although fiberglass reinforced polymer (FRP) is highly resistant to sulfuric acid, the kiln flue gas temperature of 210 °C with the raw mill off is too high for FRP. The coating for the carbon steel must be rated for the kiln flue gas temperature of 210 °C when the raw mill is off. Alloy 2205 is widely used for flue gas desulfurization (FGD) systems and provides significant corrosion resistance to condensing sulfuric acid. This application is less severe than a typical FGD system on a coal-fired boiler because the environment in an FGD absorber is wet from the slurry sprays and contains dissolved chlorides. Although the kiln flue gas contains hydrochloric acid (HCl), the HCl concentration is low and it will remain in the vapor phase and so is much less likely to attack the Alloy 2205.

3.2.2 Round Versus Square

The impacts of shape of the duct on costs were investigated. Round or square duct is feasible for this application. The budgetary costs for the shop fabrication of the duct from the kiln (before auxiliary boiler connection) are shown in Table 3.1 Duct Material Costs. These include coatings for the carbon steel. They do not include dampers or expansion joints because the costs are approximately equivalent for both types of duct. The costs also exclude supports and installation because these costs are approximately the same (i.e., within the accuracy of this phase's cost estimate). Both types of duct would require the same cranes and would be delivered to the site in the largest shipping length and welded into larger sections at grade. It is expected that the supports for a round duct would cost less than those for a square duct. Note that Alloy 2205 will allow greater support spans at smaller duct thicknesses but this is not reflected in the table below.

TABLE 3.1 DUCT MATERIAL COSTS

Material	Round Duct, $/ Linear Meter	Square Duct, $/Linear Meter
Coated Carbon Steel	$13,835	$13,066
Alloy 2205	$14,830	$17,867

*The above costs are based on: 3.4 m diameter round duct and 3.0 m x 3.0 m square duct.

3.2.3 Dampers

Dampers are needed to divert the flow from the kiln stack and from the auxiliary boiler to the CO_2 capture plant. Although a flap-type diverter damper is a possibility, the torque and shaft size requirements are excessive and the flap-type gate would require extensive duct modifications at the connection of baghouse ID Fan outlet to the existing stack, to accommodate the flap-type gate geometry. Therefore, the flue gas system design is based on using two louver dampers for each application to effectively create one diverter damper system. One of the louvers is in the duct to the stack and one in the duct to the CO_2 capture plant. The linkages of both louvers are connected to one actuator so that as one set of louvers opens, the other closes. To provide a fail-open damper to the stack, one of the following methods would be employed:

- Spring return pneumatic drives
- Pneumatic drives with accumulator tanks to provide capacity for two complete strokes in the event that the air supply was interupted
- Counterweights to open the damper to the stack

The closed damper louver is exposed to near ambient temperatures. This will result in sulfuric acid condensation on the flue-gas-exposed side of the louvers. Despite this phenomenon, seal air is not required as the damper louvers will be fabricated out of suitable corrosion resistant alloys. Alloy 2205 is the selected material. During the FEED study, further analysis on a higher-grade alloy (e.g., alloy C276, alloy 254 SMO, alloy AL6XN, alloy F255) may be considered.

3.2.4 Duct Size

Three duct diameters were evaluated at three different gas velocities to compare the increased cost of larger ducts to the decreased CO_2 capture system booster fan electricity consumption for both pond and west of 170 locations. The total installed cost of these duct sizes was estimated based on a quote for the duct materials, conceptual design for the structural steel and concrete, and historic data on installation.

The economic evaluation of the three duct sizes is shown in Figure 3.3. For the pond option a duct size with a velocity of 16 m/s was found to be most cost effective. For the West of 170 option, the evaluation indicates that a velcity less than 16 m/s should not be considered with the 22 m/s velocity having the lowest cost.

The assumptions including the acceptable payback period and the minimum velocity to keep particulates suspended should be considered in the FEED study.

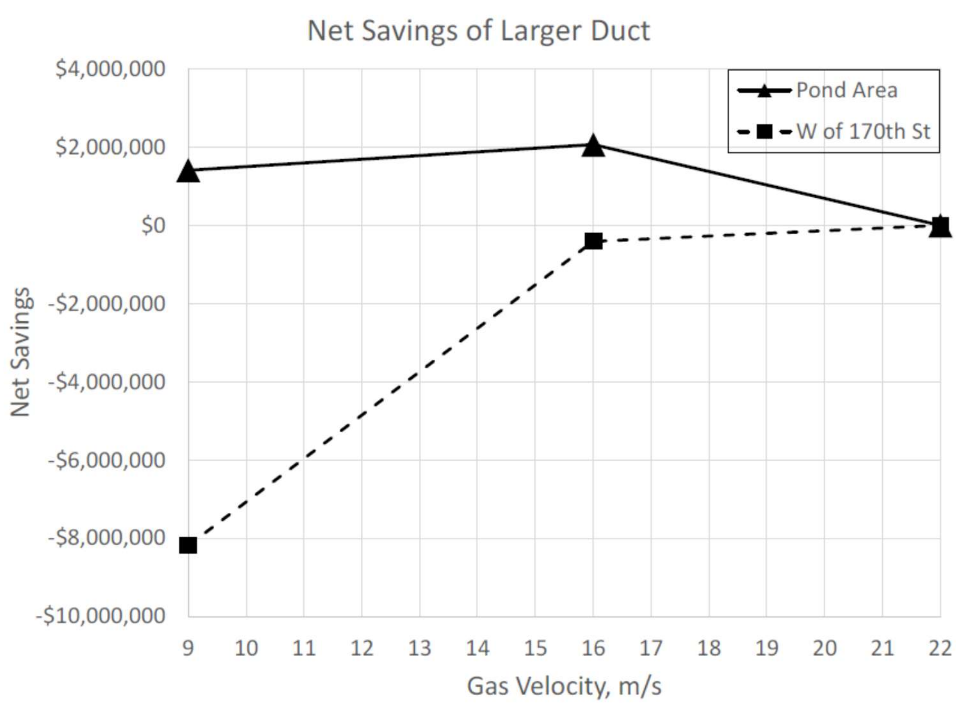


FIGURE 3.3 NET SAVINGS FOR LARGER DUCT DIAMETERS

3.3 Evaluation of Existing Kiln Baghouse ID Fan and Upstream Equipment

The ductwork and equipment upstream of the CO_2 capture plant tie-in are not significantly impacted by the CO_2 capture plant during normal operation. The CO_2 capture booster fan will draw flue gas from the existing kiln flue gas system. This results in extending the draft system of the kiln to include the CO_2 capture plant duct, blower, quencher, and absorber. The system will be sized so that the existing kiln baghouse ID fan operates close to its current operating point, with the pressure at the ID fan outlet near ambient. However, the new CO_2 capture system will require that the controls of the existing cement plant be modified to add control interfaces with the new booster fan and dampers.

Table 3.2 shows potential operating errors that could result in transient elevated positive or negative duct pressures and the possible mitigations that may be evaluated in more detail by a dynamic simulation. The configuration of the diverter damper ensures an open flow path from the kiln at all times.

TABLE 3.2 OPERATIONS AND MITIGATIONS

Operational Error	Impact	Mitigation
With the diverter damper positioned to allow flue gas to the CO_2 capture plant, the guillotine damper, or CO_2 capture train inlet damper closes	High positive pressure downstream of the existing kiln baghouse ID fan	The control system logic will prevent all dampers from being closed. Redundant limit switches and other instruments will mitigate this.
The CO_2 capture plant damper closes while the CO_2 capture plant booster fan is operating.	High negative pressure from the CO_2 capture plant booster fan	The control system logic will prevent the CO_2 capture plant booster fan from operating if the CO_2 capture plant isolation damper is closed. Redundant limit switches and other instruments will mitigate this.
The CO_2 capture plant inlet dampers close while the CO_2 capture plant booster fan is operating.	High negative pressure in the duct between the CO_2 capture plant inlet damper and the CO_2 capture plant booster fan	The control system logic will prevent the CO_2 capture plant booster fan from operating if the CO_2 capture plant isolation damper is closed. Redundant limit switches and other instruments will mitigate this.

3.4 Flue Gas Control Concept

The flue gas control system is designed to minimize impacts to the operation of the existing cement plant. Although the controls for existing baghouse ID fan and the CO_2 capture plant booster fan will be integrated to ensure stable operation, the primary controls for the baghouse ID fan will continue to operate as they were before the addition of the CCS plant. The CO_2 capture plant booster fan will control the duct pressure at the inlet to the CO_2 capture plant. The baghouse ID fan primary controls will not change, e.g., control of the baghouse pressure.

3.5 Flue Gas Duct Support Design

3.5.1 Pond Option

The flue gas ducting for the pond option has several conveyor galleries to cross over and multiple driving lanes. Tower supports, box trusses, and long-span beams are provided to support the flue gas duct and the piping and electrical tray running parallel to the duct. Most of the ducting is at a single elevation providing typical supports along the length as shown in Figure 3.4.

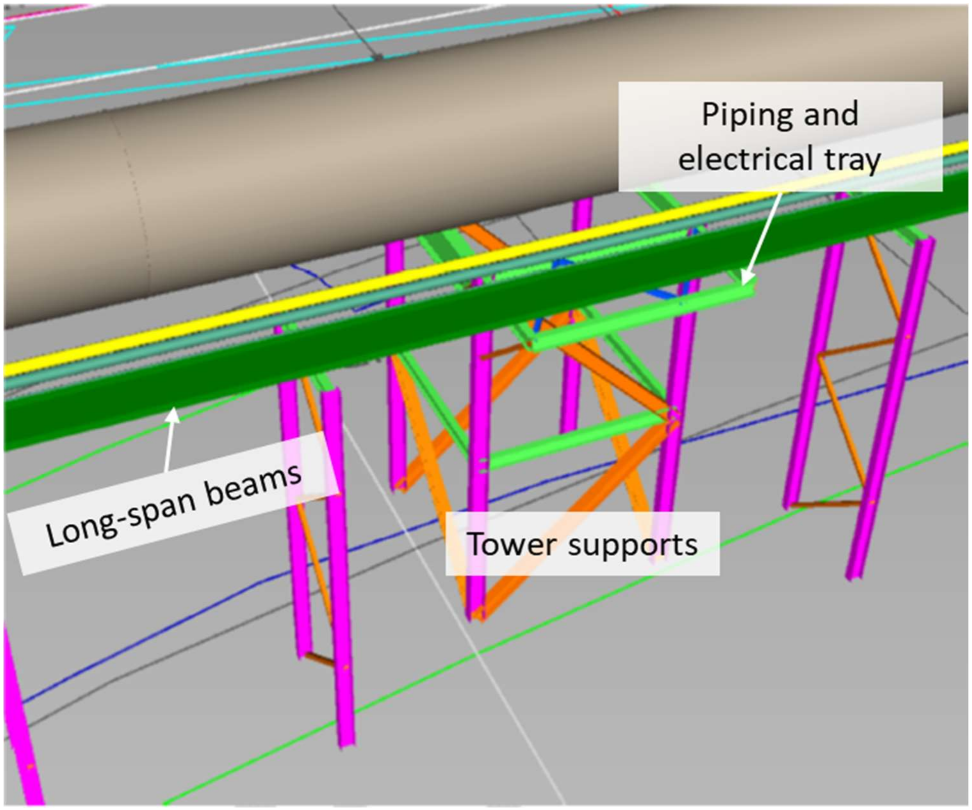


FIGURE 3.4 TYPICAL DUCT, PIPING, AND TRAY SUPPORTS

3.5.2 West of 170 Option

The flue gas ducting for the west of 170 option has fewer crossings to contend with from the existing cement plant. However, there are additional challenges to support the flue gas duct. Tower supports, box trusses, and long-span beams are provided to support the flue gas ducting and the piping and electrical tray running parallel to the duct (see Figure 3.5). These supports are provided until past the main existing plant where the duct then drops in elevation and travels closer to the ground. Once the elevation transition occurs, foundations and concrete pedestals will be provided as supports. This reduces the steel quantity required. After crossing 170 Street, the flue gas duct rises in elevation again and steel supports are again provided to allow for traffic under the flue gas duct.

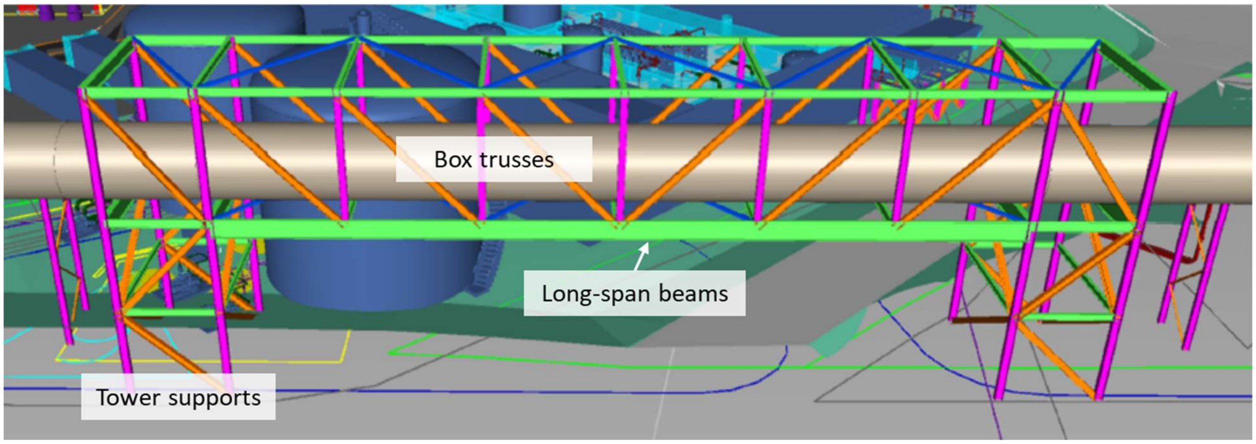


FIGURE 3.5 TYPICAL TRUSSED ROAD CROSSING

Several alternatives for the flue gas duct crossing at 170th Street were evaluated for the west of 170 site layout option. The basis for the conceptual design and cost estimate assumes routing of the flue gas duct under the 170th Street bridge with the duct supported at both sides of the bridge (see Figure 3.6). The feasibility of routing the duct over the road was discussed early in the feasibility study, but was dismissed owing to aesthetic concerns, maintenance access, and design of a steel structure to span such a long distance. An enhancement to the current design basis under the bridge, which includes modification of the bridge abutment, was evaluated and merits consideration. Both 170th Street crossing options require negotiations with and agreement by the City of Edmonton (the Owner of 170th Street and the traffic bridge). This risk and mitigation are discussed further in Chapter 14 Risks and Opportunities.

FIGURE 3.6 DUCT ROUTE TO WEST OF 170 OPTION

Chapter 4 CO_2 Capture Plant

The CO_2 capture plant was designed with a capacity to capture 95% of the total CO_2 from both the kiln flue gas and the steam supply system (auxiliary boiler) flue gas. As outlined earlier, amine absorption technology was selected for this application. Mitsubishi Heavy Industries was selected to perform this portion of the feasibility study.

The CO_2 capture plant consists of four main sections: 1) flue gas pretreatment, 2) CO_2 absorption, 3) solvent regeneration, and 4) CO_2 compression and dehydration. Figure 4.1 shows the plant configuration. Each of these sections is described in more detail below.

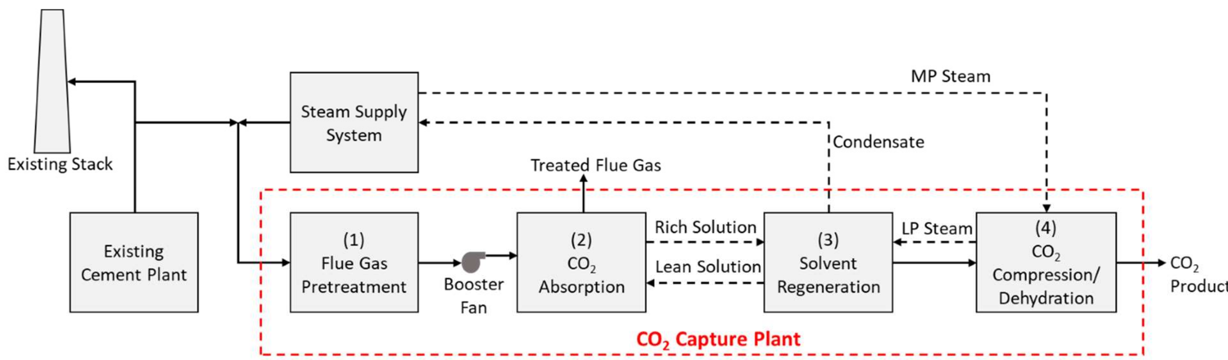


FIGURE 4.1 BLOCK FLOW DIAGRAM OF THE CO_2 CAPTURE PLANT

4.1 Flue Gas Pretreatment

Mixed flue gas from the existing cement plant and the new steam supply system first enters the flue gas pretreatment process to prepare the flue gas for efficient carbon capture. The flue gas pretreatment equipment is a rectangular tower that is comprised of two sections:

(1) flue gas quencher
(2) wet electrostatic precipitator (WESP)

4.1.1 Flue Gas Quencher

The efficiency of CO_2 absorption increases at lower temperatures, so the flue gas is cooled before it enters the CO_2 absorber. Moreover, to prevent the formation of heat stable salts in the CO2 absorber, SO2 removal is required before the flue gas contacts the amine solvent. The quencher serves two functions: (1) a flue gas cooler and (2) SO2 removal (See Figure 4.2).

Flue gas cooling and SO_2 removal take place simultaneously in the quencher. The flue gas is introduced into the quencher at the bottom and contacts with circulating caustic solution that enters the quencher at the top and is distributed on the surface of structured packing. To reduce the concentration of SO_2 in the flue gas, the circulating water is pH controlled by injecting 50 weight percent caustic soda from the caustic soda tank using the caustic soda make-up pump. The caustic solution is collected at the bottom of the quencher and recirculated through the system by the flue gas cooling water pump. The circulating water is cooled by the flue gas cooling water coolers. This cooling generates large amounts of water condensed from the flue gas. This condensate then accumulates in the tower bottom. Excess process condensate is discharged at the quencher bottom and used for the heat rejection system.

As the flue gas exits the flue gas quencher, it continues upward into the WESP to remove SO_3 and dust particles in the flue gas.

4.1.2 Wet Electrostatic Precipitator (WESP)

The WESP serves two purposes. The first is to prevent adverse impacts caused by SO_3 in relation to amine emissions from the top of the CO_2 absorber. The second benefit of the WESP system is that it removes dust from the flue gas stream which can contribute to degradation of the solvent and fouling of the carbon capture equipment. To ensure the collecting electrodes are clean at all times, which maintains high SO_3 and dust removal efficiency, intermittent washing of the WESP is undertaken by the caustic soda containing liquid from the flue gas cooling water pump.

A flue gas blower is required to draw the flue gas from the existing plant and the steam supply system to overcome the pressure drop across the flue gas quencher and CO_2 absorber. It is installed upstream of the CO_2 absorber.

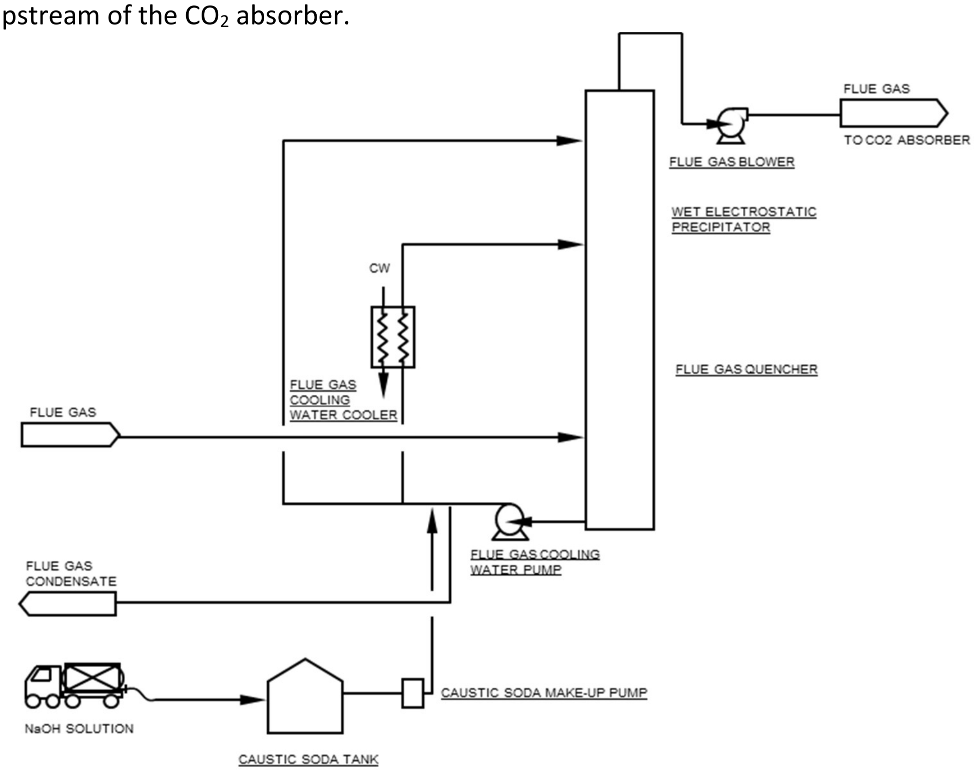


FIGURE 4.2 FLOW DIAGRAM FOR FLUE GAS PRETREATMENT

4.2 CO_2 Absorption

The CO_2 absorber consists of a rectangular tower with dimensionally configured structured packing. The proposed CO_2 absorber has two sections: (1) CO_2 absorption section at the bottom and (2) flue gas washing section at the top (see Figure 4.3).

4.2.1 CO_2 Absorption Section

The purpose of the CO_2 absorption section is to allow the flue gas to contact the amine solution so that the CO_2 can be absorbed. Since this process takes place at the amine film surface, increasing the surface area of the amine that is available for absorption is key to promote efficient CO_2 removal. This is accomplished by filling the absorption section with structured packing. The cooled flue gas exiting the flue gas pretreatment process is introduced into the bottom of the CO_2 absorber and flows upward through the structured packing. Amine solvent (KS-1™) with low CO_2 loading, often termed "lean amine," is supplied at the top of the absorption section and moves downward through the packing. The flue gas contacts the solvent in a countercurrent fashion at the surface of the packing, where 95% of the CO_2 in the flue gas is absorbed by the solvent. Solvent containing absorbed CO_2 moves down the absorber tower. This solvent is often termed "rich amine." Rich amine solvent collects at the bottom of the CO_2 absorber before being pumped through a heat exchanger by the rich amine solution pumps to the top of the Regenerator.

The CO_2 absorption process is exothermic, resulting in a temperature increase as the solvent travels down the CO_2 absorber. The absorber tower is equipped with an intermediate cooling section to enhance CO_2 absorption performance, which is more effective at lower temperatures.

4.2.2 Flue Gas Washing Section

The flue gas exits the CO_2 absorption section with reduced CO_2 and slightly elevated temperature due to the exothermic nature of the absorption process, and it enters the washing section to again reduce the flue gas temperature and to maintain the water balance. The washing section also removes residual amine droplets and vapor that may become suspended in the gas flow.

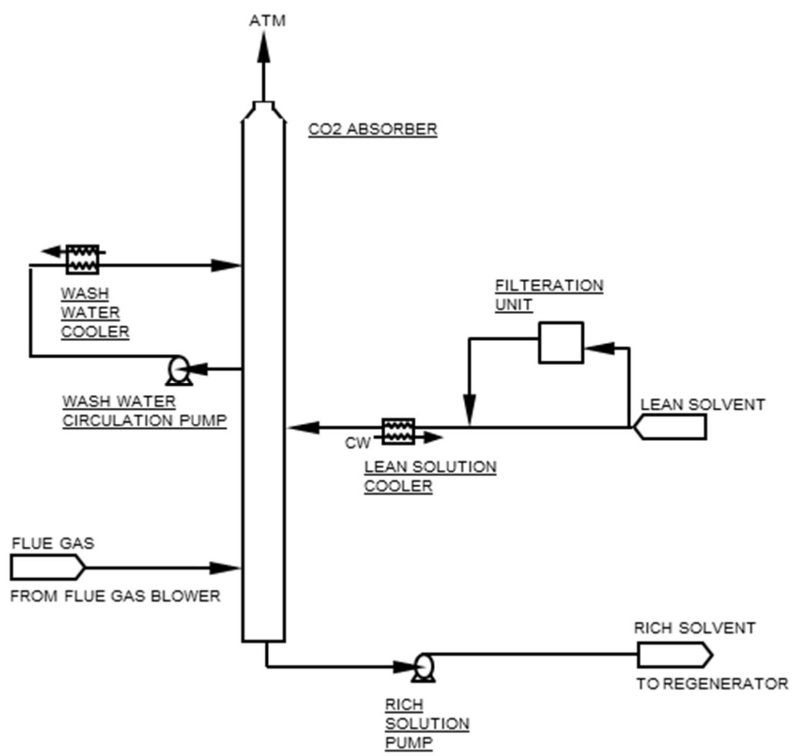


FIGURE 4.3 CO_2 ABSORBER

4.3 Solvent Regeneration

Solvent based post combustion capture processes exploit the reversible nature of the CO_2-amine molecular bond. The bond formed between the molecules is broken through the application of heat, which occurs in the CO_2 regenerator. The proposed CO_2 regenerator is a cylindrical column with structured packing. The regenerator reboiler provides the heat required to break the CO_2-amine bond which drives the separation of CO_2 from the rich solvent by steam-stripping.

- Rich solvent exiting the bottom of the absorber is preheated by lean amine exiting the bottom of the regenerator using the lean-rich solution heat exchanger. This preheated rich solvent is introduced into the upper section of the Regenerator. Low pressure steam from the steam drive of the CO_2 compression unit is supplied to the regenerator reboiler to provide heat. This steam vapor moves up the regenerator column, contacting rich solvent that is flowing downward in a countercurrent fashion. The introduction of heat desorbs CO_2 from the rich solvent, and the lighter CO_2 flows up the column along with the steam vapor, while the heavier liquid solvent solution moves down.
- The lean solvent from the bottom of the regenerator column is sent back to the CO_2 absorber by the lean solution pump.

Overhead vapor from the regenerator, which is comprised primarily of steam and CO_2 is cooled by the CO_2 gas condensing unit in order to condense the steam to water, which is collected from the bottom of the vessel, and returned to the regenerator, leaving a pure CO_2 product, suitable for compression and subsequent transport and storage.

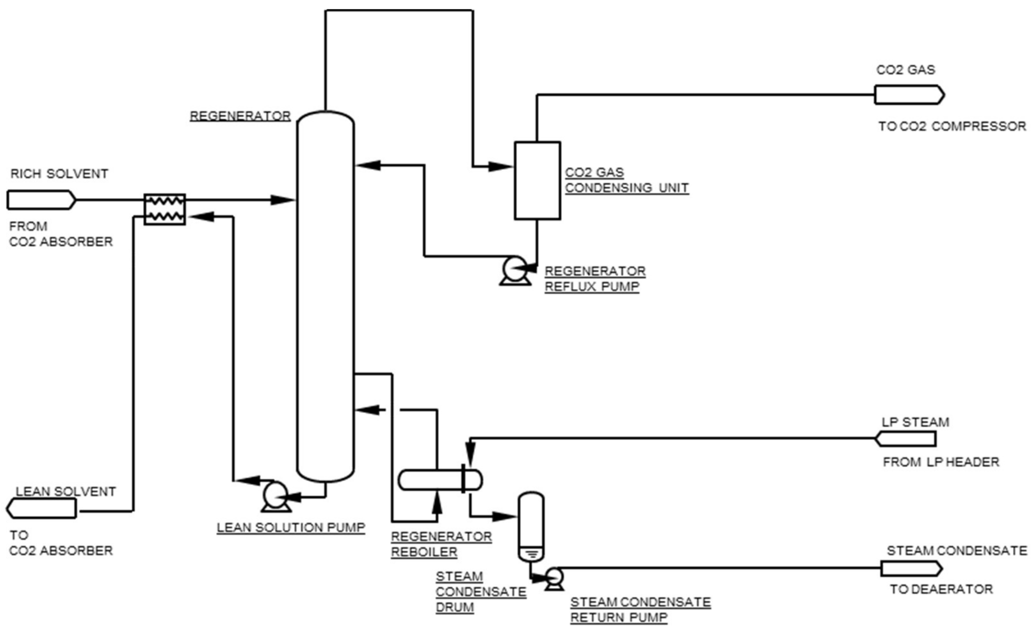


FIGURE 4.4 CO_2 REGENERATOR

4.4 CO_2 Compression and Dehydration

Following the capture process, the CO_2 gas is compressed above super critical conditions to a specified pressure of 179 barg before transport through a pipeline. The CO_2 compressor is steam-driven and requires medium pressure (MP) steam which is sourced from an auxiliary steam generator. After being utilized to drive compression, the MP steam is reduced to LP steam. This LP steam flows to the CO_2 capture process and enters the regenerator reboiler to provide the required amine regeneration energy. Once it passes through the regenerator reboiler, the steam is further reduced into condensate.

The CO_2 compression unit consists of low pressure (LP) and high pressure (HP) compression sections. A CO_2 Dehydration Unit utilizing a triethylene glycol (TEG) process is installed between the LP and HP compression sections to remove moisture from the CO_2 gas. The LP CO_2 compression section has multiple stages, collectively referred to as "wet-stage" compression due to the high moisture content in the CO_2 gas and the need to remove heat created by the compression process. Interstage coolers are installed between each of the compression stages to cool the CO_2 and remove moisture from the partially-compressed CO_2. The CO_2 exiting the TEG dehydration unit is introduced into the HP compression unit which is referred to as "dry-stage" compression. After HP compression, the supercritical CO_2 is cooled by the final stage discharge cooler and delivered to the pipeline for transportation.

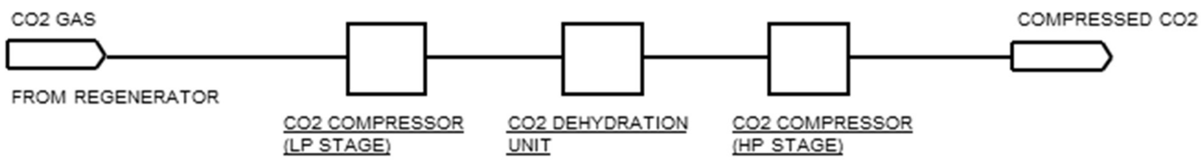


FIGURE 4.5 CO_2 COMPRESSOR

4.5 Amine Health

4.5.1 Solvent Filtration

Filtration equipment is included in the design to achieve continuous removal of particulate matter from the CO_2 solvent. Particulate matter that accumulates in the system may cause amine degradation as well as corrosion and fouling in the CO_2 removal equipment.

4.5.2 Solvent Storage and Makeup

The system includes a storage tank and pumps to ensure solvent levels are kept constant during operation and to allow a mechanism to replace degraded solvent as required.

4.5.3 Solvent Reclaiming

Reclaiming removes solvent degradation products, such as heat stable salts, soluble iron, and suspended solids, from the solution system. Steam provides most of the heat required for reclaiming, and reflux water is also used to assist in boiling the solvent. Caustic soda solution is added to the reclaimer drum to break down the heat stable salts and recover the pure KS-1™ bound to the salts. During this recovery process, the impurities eventually become concentrated which hinders removal efficiency. At this point the impurities are discharged to the reclaimed waste tank.

4.6 Automatic Load Adjustment Control System

The cement plant operation changes according to the product rate and fuel source, which results in fluctuating flue gas conditions such as flow rate and CO_2 concentration. The automatic load adjustment control system for the CO_2 capture plant is developed to maintain optimized operation while following the dynamic flue gas condition of the host plant. This control system reduces the amount of manual actions by the CO_2 capture plant operators and provides flexibility in the level of attention needed to monitor the CO_2 capture plant operating parameters. The solvent circulation flow rate and steam flow rate supplied to the regenerator reboiler are changed automatically by controlling the difference between the actual measured value and the target value of the CO_2 recovery rate or CO_2 capacity within a predetermined range. Therefore, even if the CO_2 concentration in the flue gas changes significantly, the desired CO_2 recovery ratio, capture amount, and steam consumption rate can be safely maintained.

4.7 Equipment Redundancy and Isolation

Equipment redundancy and isolation are considered for and installed on equipment whose functionality is vital in achieving continuous process operations. Implementing redundancy is also favorable for equipment susceptible to frequent fouling. Identifying equipment requiring redundancy and isolation is essential in increasing the reliability of future CCS installations. The cost of installing redundant equipment is greatly reduced if it is part of the original design basis instead of a later retrofit.

In this project, the redundant items include:

- Wash water cooler,
- Lean solution cooler,
- Solution heat exchanger,
- Lean and rich solution pumps, and
- Caustic soda make-up pumps.

Chapter 5 Heat Rejection

Integrating the Lehigh Cement Plant with a CO_2 capture and compression process increases the heat rejection load and adds a new water discharge stream to the plant. In order to provide cooling to the CO_2 capture plant and maintain the water balance of the existing Lehigh plant, a new heat rejection system was designed and included air cooled heat exchangers (ACHE) and wet surface air coolers (WSAC) placed in series to form a hybrid dry and wet cooling system. This is illustrated in Figure 5.1 below. Two different configurations of the hybrid cooling system were evaluated, a Single and a Dual Loop Hybrid Cooling System. The second or exterior loop in the dual loop cooling system was filled with glycol to provide freeze protection.

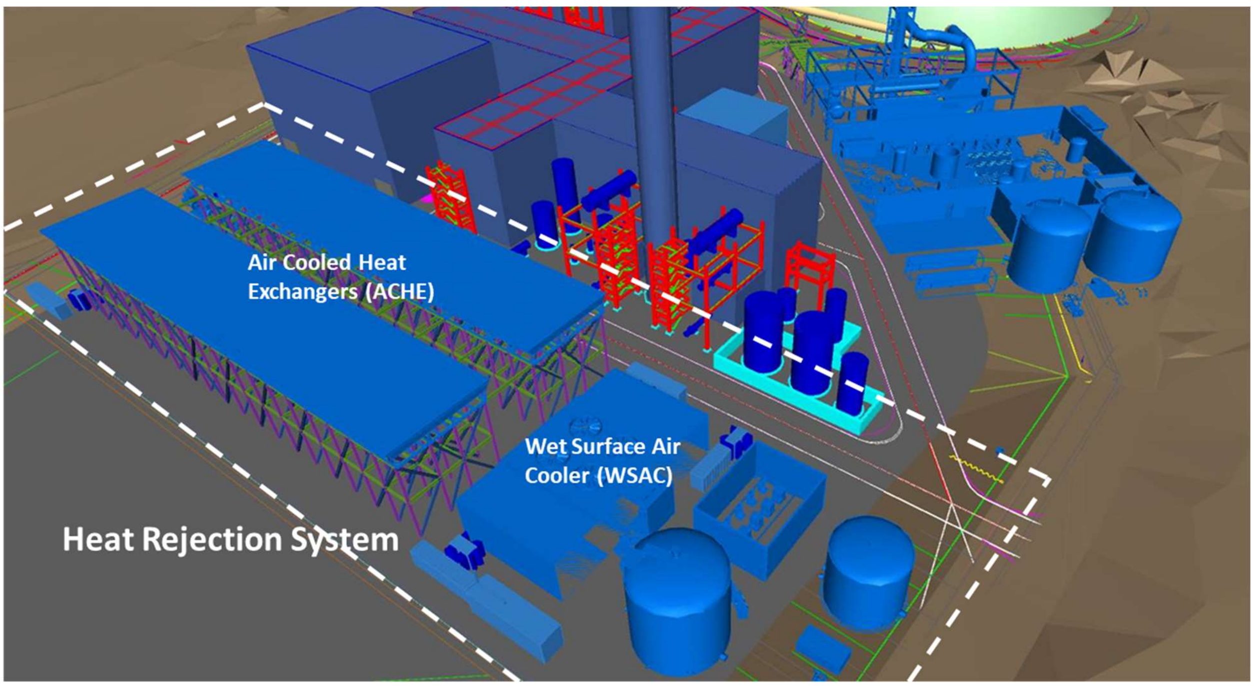


FIGURE 5.1 3D GRAPHICS FOR HEAT REJECTION SYSTEM

5.1 Heat Rejection Duties for CCS and Liquid Discharge Streams

The addition of CO_2 capture and compression processes introduces new heat rejection loads and new water discharge streams. The additional cooling load is attributed to the duties of flue gas inlet cooling, absorber flue gas exit wash water cooling, duties associated with the CO_2 absorber and solvent regenerator and the cooling duties for CO_2 compression and dehydration. The main water discharge from the CO_2 capture plant is flue gas condensate generated in the flue gas quencher when the flue gas is cooled before being introduced to the CO_2 absorption process. The flue gas condensate must be utilized to avoid creating a waste water stream that would need to be treated and managed to maintain the neutral water balance of the site. Table 5.1 summarizes the CO_2 capture plant heat rejection loads, the cooling water temperatures and the flue gas condensate stream flows used in the heat rejection system design.

TABLE 5.1 PARAMETERS USED IN HEAT REJECTION SYSTEM DESIGN

Parameters	Design Condition	Operating Condition
Heat Rejection Load (MWth)	175	150
Cooling Water Temperature (˚C)	25	25
Cooling Water Return Temperature (˚C)	40	38

5.2 Heat Rejection Configurations

Two configurations of hybrid cooling system were considered in this study. The first configuration is a closed single loop hybrid cooling system which uses demineralized water as cooling medium. The later configuration is dual loop hybrid cooling system which integrates a demineralized water loop with a glycol loop for freeze protection. Both configurations utilize an ACHE in series with a WSAC as the heat rejection equipment.

5.2.1 Single Loop Hybrid Cooling System

The process flow diagram of the single loop hybrid cooling system is shown in Figure 5.2. Demineralized water with corrosion inhibitors is used for the process fluid in the closed cooling loop. This cooling water is pumped to the CO_2 capture plant. The hot return cooling water is then introduced to the ACHE and the WSAC. Makeup water to the WSAC is taken from flue gas condensate. Before being introduced to the WSAC, the flue gas condensate is treated to improve its quality which allows the cycles of concentration in the WSAC to be maximized. An expansion tank is required at the pump suction to provide the necessary volume for process fluid expansion due to the change in fluid temperature. All outdoor piping is insulated and heat traced to prevent damage to piping and equipment during freezing temperatures. The WSAC basin is equipped with basin heaters to prevent the basin from freezing and the WSAC open loop circulating water system can continue operation to prevent the demineralized internal water from freezing during short shutdowns. When ACHE bays are isolated from operation, or if the ACHE in whole is not in operation for extended periods during freezing temperatures, the ACHE bays and WSAC internal loop must be drained to avoid damage to the heat transfer surface and tubes.

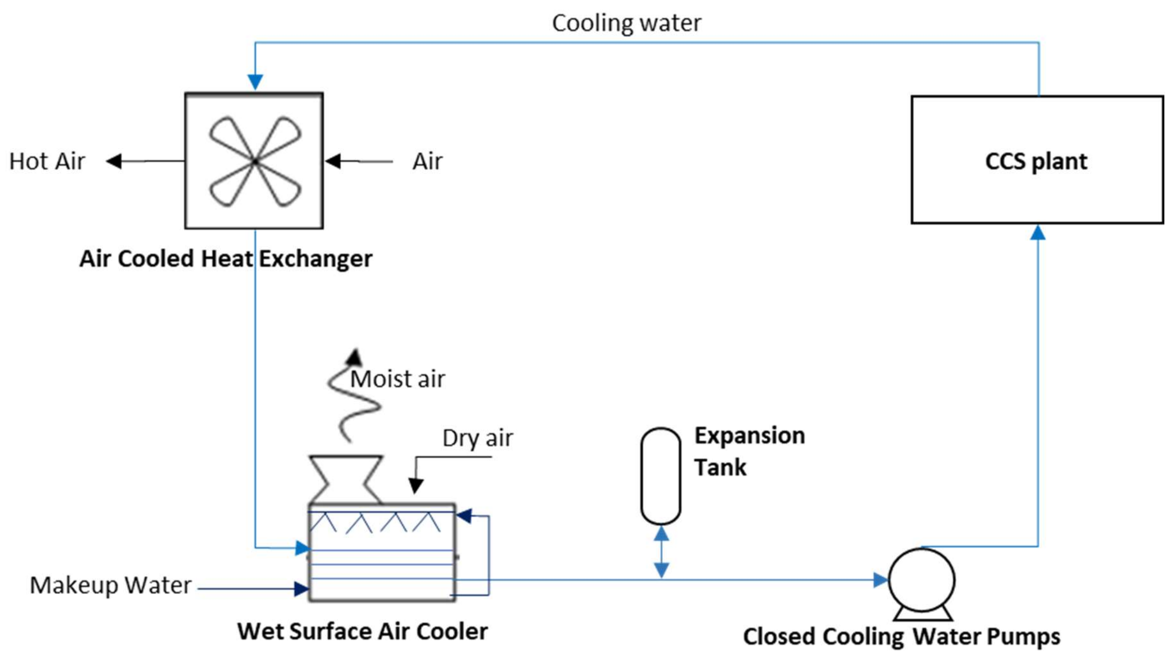


FIGURE 5.2 SIMPLIFIED FLOW DIAGRAM OF SINGLE LOOP HYBRID COOLING SYSTEM

5.2.2 Dual Loop Hybrid Cooling System

The dual loop hybrid cooling system integrates demineralized water with corrosion inhibitors and glycol loops using plate and frame heat exchanger (PFHE) as shown in Figure 5.3. This system consists of an ACHE, WSAC, and a PFHE in series as a means to reject heat from the CO_2 capture plant and related equipment. The demineralized water loop is fed by closed cooling water pumps that send demineralized water through the plate and frame heat exchangers and the CCS equipment. The CO_2 capture plant cooling loop requires an expansion tank to handle fluid expansion for process fluid temperature changes. On the other side of the plate and frame heat exchangers, the glycol loop is fed by another set of closed cooling water pumps that provide process fluid to the ACHE, WSAC, and the plate and frame heat exchangers. Glycol is used in closed loop systems to prevent damage from freezing temperatures. Except for the open loop circulating water system in the WSAC, glycol provides the major operational benefit of not having to drain piping and equipment in the cooling system when equipment is isolated or the system is shut down during freezing temperatures. A 55% glycol solution is recommended for the Edmonton area which can have temperature excursions to -50 ˚C. Both the single loop and dual loop options will require that a small amount of cooling medium be sent to the sample panel for sample cooling.

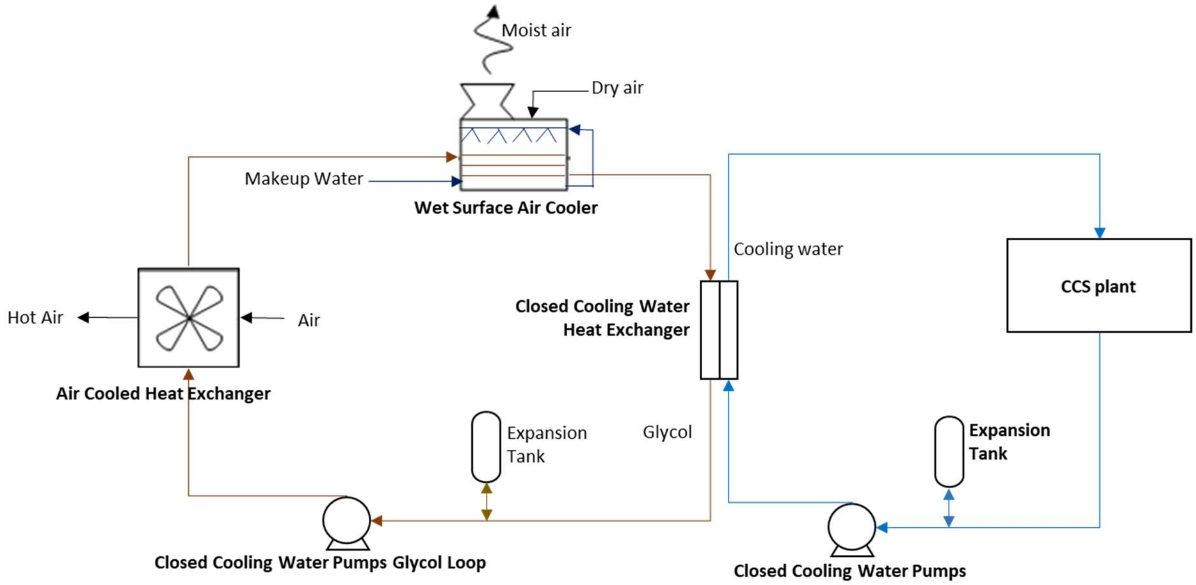


FIGURE 5.3 SIMPLIFIED FLOW DIAGRAM OF DUAL LOOP HYBRID COOLING SYSTEM

5.3 Plume Abatement

To reduce the visibility of the WSAC plume, plume abatement configurations were evaluated. The WSAC plume can be mitigated by a few different mechanisms which are summarized below.

5.3.1 Partial Wet/Dry Operation

Spray water over one of the tube bundles is turned off to promote heating of the air leaving the plenum and lowering of its relative humidity. This is best used during times when the WSAC is operating at wet bulb temperatures below the design wet bulb temperatures. Implementing this type of plume abatement at full load design conditions could result in a WSAC performance shortfall.

5.3.2 Cold Air Introduction

Cold air is introduced through a series of louvers and into the WSAC plenum causing some of the water vapor to condense, lowering the absolute humidity of the saturated air stream. Further investigation with manufacturers suggests that previous experience implementing this type of plume abatement control can be somewhat unreliable. This control will have an impact on the plume, but could be less effective than other techniques and is not recommended for the Lehigh Cement Plant application.

5.3.3 Re-Heat Coils

A reheat coil is installed in the WSAC plenum and is used to heat the saturated air stream which will reduce the relative humidity. The coils can be heated with steam, hot water, or electricity. Reheat coils are recommended for the Lehigh Cement Plant application for plume abatement.

The heat for the reheat coils would be obtained from a slip stream of warm closed cooling water taken from the return cooling water from the CO_2 capture plant heat exchangers, upstream of the ACHE. The water used for the heating coil would then be directed to the inlet of the WSAC for further cooling.

Given the proximity of the WSAC to surrounding roads and railways in addition to the CO_2 capture plant (and the Lehigh Cement Plant with the pond option), and to maintain the best performance possible from the WSAC, it is recommended that the WSAC be equipped with a plume abating heating coil as recommended by the manufacturer for this application.

5.4 Variable Frequency Drive Economic Evaluation

The ACHE and WSAC fans were evaluated using both constant speed and variable speed fans via the use of variable frequency drives (VFDs). The relative capital cost of installing the VFDs was compared to the savings in operating expenses over a 30 years period. Fan affinity laws, motor efficiencies, drive efficiencies, fan efficiencies, fan stall points, heat transfer coefficients, VFD efficiencies, and air density with temperature were variables used to ascertain the power saved by utilizing VFDs to reduce fan speed of all fans, and thus air flow, vs. turning off constant speed fans to provide the necessary turndown. It is recommended to equip each ACHE bay (three fans) and each WSAC with VFD drives.

Figure 5.4 illustrates the overall hybrid cooling system power demand on a monthly basis when considering average monthly ambient conditions at the design heat duty. It includes all major loads for the hybrid cooling system including the closed cooling water pumps and the WSAC open loop circulating water pumps in addition to the WSAC and ACHE fans. Additional power savings would be realized at off design duty conditions and are not part of this evaluation.

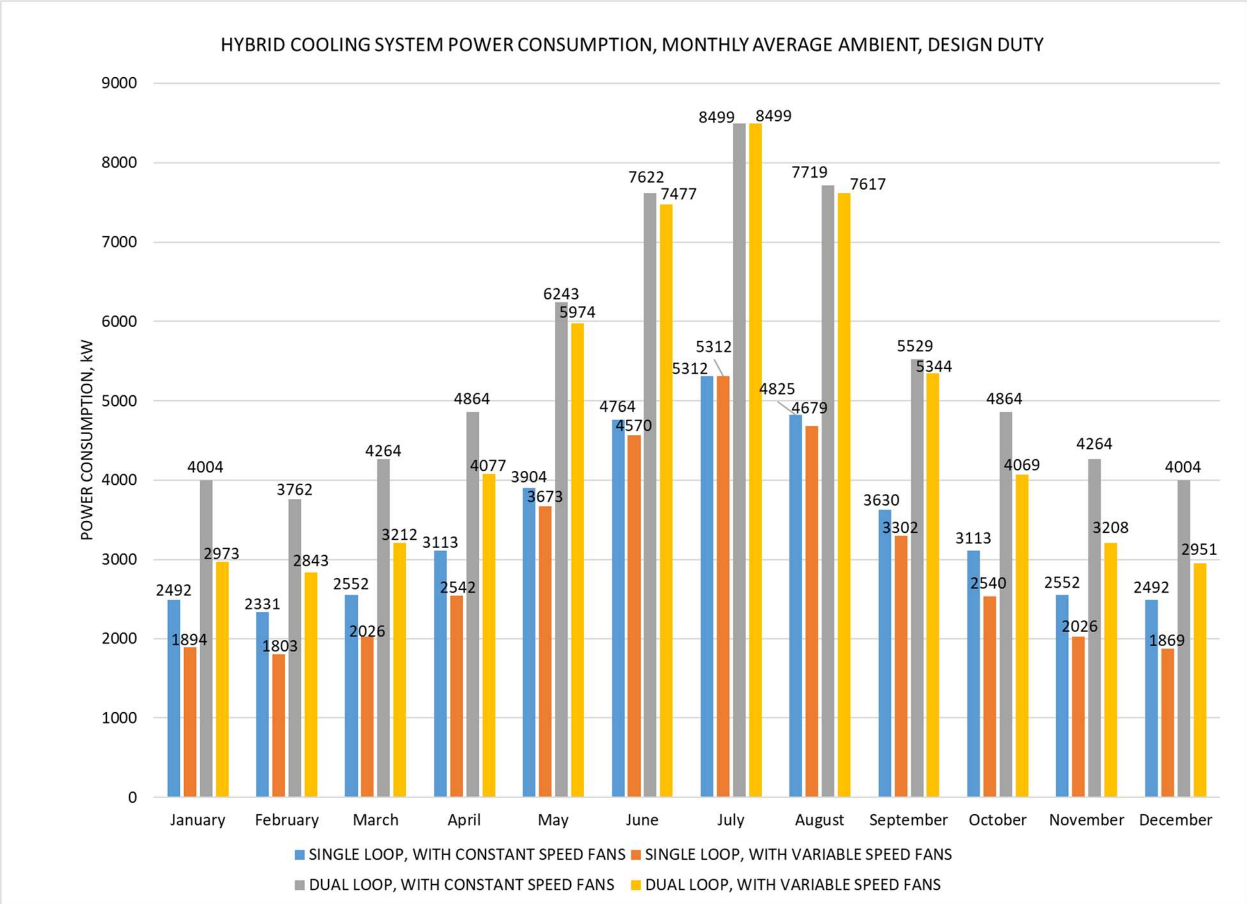


FIGURE 5.4 HYBRID COOLING SYSTEM POWER CONSUMPTION

The addition of VFD drives incurs a higher capital cost when compared to constant speed fans for the ACHE and WSAC. Table 5.2 summarizes the economic analysis of the VFD evaluation. The estimated payback period is below three years in both cases.

TABLE 5.2 VFD EVALUATION

Cooling Loop Type	VFD Cost (Adder)	Annual kW Savings	NPV Of Fan Power	Net Savings	Payback Period, Years*
Single loop	$890,000	$311,861	$4,603,026	$3,717,246	2.8
Dual loop	$1,350,000	$544,129	$8,031,265	$6,679,285	2.5

* The payback period is the VFD cost adder divided by the annual power savings.

5.5 Hybrid Cooling System Arrangement

The evaluation of both the single and dual cooling loop arrangements for both the pond and west of 170 options shows that for the pond option there is sufficient space to locate the single loop option west of the CO_2 capture plant and between the CO_2 capture plant and the new detention pond. The detention pond east bank will be located 15 feet west of the ACHE. However, for the dual loop option, there is not enough space to locate the hybrid cooling system in the pond option since the ACHE must grow in bays (38 to 58 bays) and a second WSAC must be provided to compensate for additional approach temperature between the two cooling loops. There will be a conflict with the detention pond. For the west of 170 option, there are no space constraints for either the single loop or dual loop arrangements.

5.6 Conclusions and Recommendations

A single cooling loop configuration has several advantages over a dual loop configuration. The single loop heat rejection system required a smaller equipment footprint, lower auxiliary power usage, and provided better performance at high ambient conditions. The single loop configuration also required less heat transfer equipment. This is partially offset by the expense of extensive freeze protection (installed freeze protection and operational freeze protection) necessitated by the use of demineralized water as the process fluid. The single loop configuration was also feasible for both the pond option and west of 170 option while the dual loop configuration is not feasible for the pond option due to conflicts with the space needed for the new detention pond. The study recommended a single loop cooling system.

Plume abatement options are available for the WSAC. The most promising option is to utilize a WSAC reheat coil in the WSAC plenum to lower the relative humidity of the exiting saturated air.

The use of variable speed fans for WSAC and ACHE cooling in lieu of on/off control functionality utilizing constant speed fans to maintain desired cold water temperature shows a relatively short payback period and is recommended.

Chapter 6 Electrical Instrumentation and Controls

The addition of CO_2 capture plant and BOP systems to the Lehigh plant requires significant electrical infrastructure to support the new electrical loads. The existing facility's electrical system does not have adequate capacity to support all the new equipment and loads. This chapter presents the evaluation of electrical options for the CO_2 capture plant and BOP systems for both the pond and west of 170 sites.

6.1 Existing System and Constraints

The existing cement plant is fed by one 138 kV EPCOR Distribution and Transmission Inc. (EPCOR) overhead radial transmission line connecting into two 138/4.16 kV, 15/20/25 MVA transformers at the local cement plant substation. The substation was conceived 40 years ago to have 100% redundancy but due to the main electrical switchgear and transformers kVA ratings, and plant load increases over the years, one transformer is insufficient to power all of the cement plant. A new interconnection to the local power utility (EPCOR) will be required for the CCS Plant.

The existing cement plant is controlled by two separate process control systems. Although the CO_2 capture process control system (PCS) should be based on Siemens PCS 7 to ensure plant maintenance and support familiarity, the new human machine interface (HMI) should be located in a new dedicated control room. The new PCS will be broken down by CO_2 capture units and associated other new process areas.

The current peak demand forecast varies between 11 and 15 MW so the interconnection could be at distribution or transmission level. Some assumptions were made regarding the most likely interconnection option at the transmission level and in house cost estimates were developed by the BOP consultant. The pond option substation layout was assumed to tie-in to a new transmission line running north-east to south-west along the north side of the pond option. The transmission line would be sourced from an EPCOR substation 6 km away. The west of 170 substation layout was assumed to tie-in to a transmission line coming from the east direction and sourced from the same EPCOR substation 8 km away.

6.2 Scope

The scope of this work package includes evaluation of two (2) electrical options for the carbon capture and associated equipment. The two (2) options, required because two different locations were being considered in the study, included an option with pond water pumps utilizing two (2) motor control centres (MCCs) and an emergency diesel generator (EDG) and an option with a separate admin building feed.

6.2.1 Equipment Common

The electrical system includes specific equipment for both options and some common equipment shared between the two. The common equipment includes the following:

- Two (2) 138/4.16kV transformers
- One (1) 4.16kV MHI feed
- Two (2) 4.16/0.48kV MHI transformers
- Four (4) ACHE 4.16/0.6kV transformers with respective motor control centers (MCC)
- One (1) 4.16/0.6kV wet surface air cooler (WSAC) transformer with respective MCC
- One (1) 4.16/0.6kV waste heat recovery unit (WHRU) transformer with respective MCC
- Three (3) 4.16kV closed cooling water (CCW) pumps

- Two (2) 4.16kV auxiliary boiler feed pumps
- One (1) 4.16/0.6kV low voltage switchgear transformer
- Two (2) 0.6kV BOP MCCs
- One (1) 0.6kV aux boiler feed
- Two (2) 0.6kV air compressors

6.2.2 Pond Option Specific Equipment

The pond option consists of specific electrical equipment that includes one (1) 4.16/0.6kV POND transformer with respective MCC, one (1) 0.6kV POND MCC, one (1) auto transfer switch, and one (1) emergency diesel generator. This option has four (4) pond pumps that require an emergency diesel generator and auto transfer switch as during a blackout condition the pond could overflow. This option does not require the addition of an admin building since it is located relatively close to the existing site.

6.2.3 West of 170 Option Specific Equipment

The west of 170 option consists of specific electrical equipment that includes a single (1) 0.6kV admin building feed. The addition of the new admin building is necessary for this option since this new site is located a significant distance from the existing site.

6.2.4 System Design

Power at 138kV is brought into two (2) 138kV/4.16 kV transformers before connecting to the medium voltage (4.16 kV) buses. Power is then sent to the CCW pumps, aux boiler feed pumps, ACHE transformers, MHI transformers, WSAC transformer, WHRU transformer, and low voltage switchgear transformer. The low voltage transformer sends power to the air compressors and the BOP MCC.

6.2.4.1 Pond Option Design Conditions

The electrical design conditions for the pond option adds to the above design by including a medium voltage and low voltage transformer for the pond pumps and equipment. The low voltage transformer is also backed up by an EDG. Ninety (90) kW would also have been added to the WSAC MCC for the heat tracing associated with the WHRU; the WHRU could not be economically justified so the load was not included.

6.2.4.2 West of 170 Option Design Conditions

The electrical design conditions for the west of 170 option adds to the above design by including a feed for an admin building. This building is necessary as the west of 170 option is located a considerable distance from the existing plant.

6.2.5 Substation Layout

Each option has a unique substation layout. The pond option substation layout has a tie-in location facing towards the north-east. The transmission line length needed for this option is approximately 6 km. The west of 170 substation layout has a tie-in location facing towards the east. The transmission line length needed for this option is approximately 8km. See Figure 6.1 below for the detailed transmission line route.

Both options have several items included in the cost estimate. These include single circuit transmission line, wooden frame structures, the contractor to provide the final structure outside of the substation, and cable is provided to connect to a dead end structure inside of the substation.

FIGURE 6.1 TRANSMISSION LINE ROUTE

6.2.6 Electrical Enclosure Layout

There are two main electrical enclosures for this project and both options utilize the same enclosure layouts. The first electrical enclosure (ENC-BOP-01) contains the majority of the BOP systems, the MV main and tie breakers, as well as the low voltage switchgear. The battery system and UPS system is also located in this enclosure along with BOP MCC A. The second electrical enclosure (ENC-BOP-02) contains the water treatment programmable logic controller (PLC) as well as BOP MCC B.

6.2.7 System Analysis

A system analysis study was done for both the pond option and the west of 170 option. This analysis evaluated the load flow, short circuit, and motor starting performance for each option. Two different breaker configurations were used, both main breakers in operation as well as a single main breaker and the tie breaker in operation. Different source voltage levels were also considered, one at 100% and one at 95%.

The load flow study shows the operating voltages and operating currents of all equipment. The study confirmed that the electrical system would perform within standard requirements under normal and abnormal scenarios.

6.3 Electrical Demand

The electrical demand loading for both pond and west of 170 options is shown in Figure 6.2. It also presents an analysis of monthly electrical consumption. This analysis uses the monthly demand values for the ACHE fans, WSAC fans, and cooling pumps from Alfa Laval. The air compressors, water treatment, pond pump equipment, aux boiler, WHR boilers, admin building, MHI loading, and miscellaneous loads are all approximated on a monthly basis based on a constant load according to the load list. The heat rejection monthly demand is based proportionally on the percentage of total ACHE load being used for a given month. The heat trace monthly demand is based inversely on the percentage of total ACHE load being used for a given month. These monthly system values are then summed up to produce a total kW demand load for every month as shown in Figure 6.2.

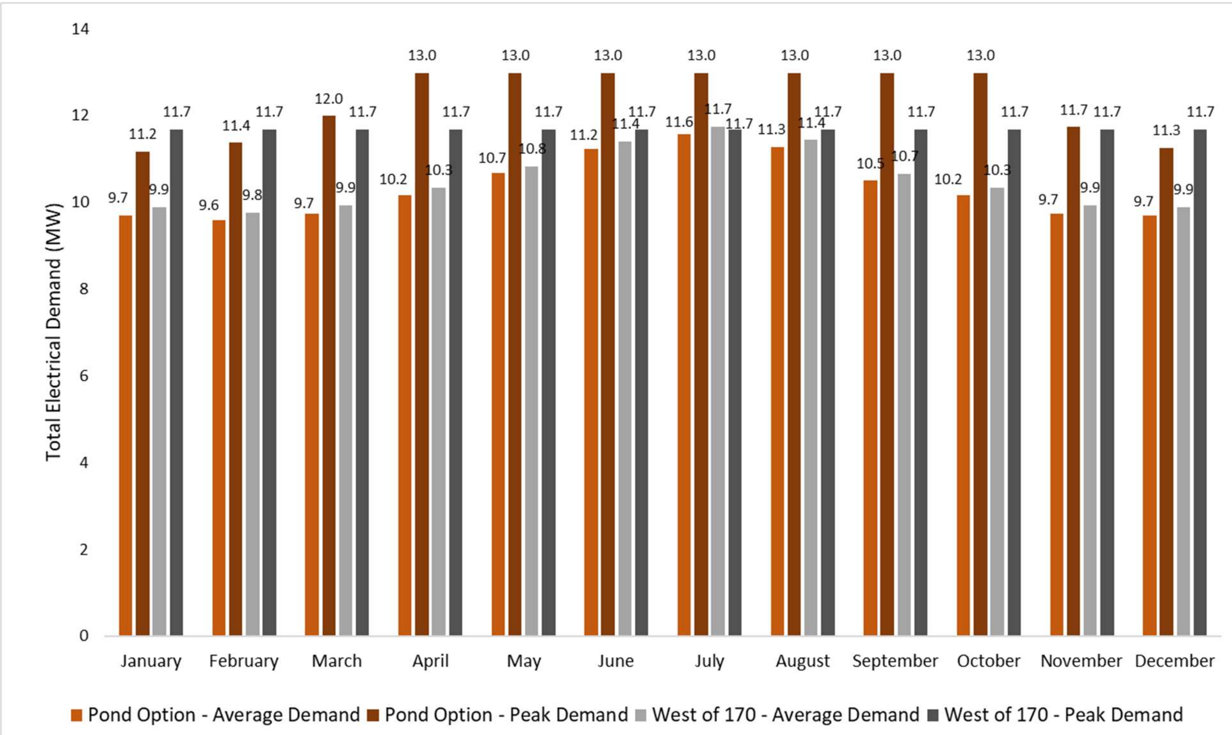


FIGURE 6.2 ELECTRICAL DEMAND – TOTAL kW

6.4 Plant Communications

The communications system covers five (5) major plant areas. Each of these areas contain fiber patch panels that allow the distributed control system (DCS) communication. The main hub for the plant communications is the MHI control room. The water treatment operator workstation and water treatment engineering workstation are both located in this area. The fiber connection to the existing plant also connects at this location.

There are four (4) remote DCS input output (IO) cabinets located in two main areas in the plant. The BOP electrical enclosure contains three (3) of these cabinets and the water treatment building contains one (1) cabinet. These cabinets connect to the corresponding fiber patch panels in their respective areas and are routed back to the MHI control room.

Seven (7) PLCs are located throughout the plant areas. The water treatment and air compressor PLCs are located in the water treatment building, the aux boiler CEMS and fuel gas system PLCs are located in the aux boiler building, and the standby diesel generator PLC is located on the standby diesel generator. Each of these PLCs is connected to a network switch in their corresponding area which is in turn connected to a fiber patch panel and routed back to the MHI control room.

The individually enclosed MCCs also have their own fiber patch panels. Each of these has a single trunk cable that is routed back to the MHI control room.

All fiber connections are assumed to be ST multi-mode type connectors. Trunk cables are composed of individual strands of either six (6) or twelve (12) fibers apiece. These trunk cables include 20% to 30% spare fibers.

6.5 Conclusions and Recommendations

The system analysis showed that the designed power system is capable of handling various configurations and conditions with some tapping done to several of the transformers.

Provisions for emergency power have been provided for both options. The battery backup is the primary source of emergency power for both options. For the pond option, a secondary source of emergency power comes from an EDG. This allows the pond pumps and other various equipment to operate during a power outage.

Chapter 7 Heat Integration

Steam is required by the CO_2 capture and compression process to drive the CO_2 compressor and for use in the amine regenerating and reclaiming process. A natural gas fired auxiliary boiler was selected to provide steam to the CO_2 capture plant. The concept of utilizing waste heat from the existing Lehigh plant to also produce steam, thereby reducing the amount of steam required from the auxiliary boiler which would also reduce the amount of CO_2 produced by the auxiliary boiler was also studied. Figure 7.1 presents an overview of the steam supply system.

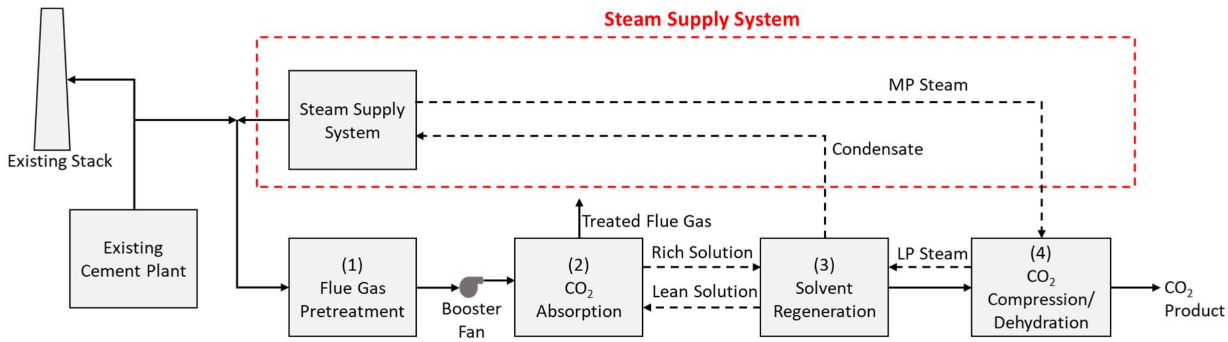


FIGURE 7.1 SIMPLIFIED DIAGRAM OF CO_2 CAPTURE AND COMPRESSION PROCESS WITH STEAM SUPPLY SYSTEM HIGHLIGHTED

7.1 Steam Requirement and Design Basis

This study included a steam-driven CO_2 compressor which requires medium pressure (MP) steam, while the capture plant requires low pressure (LP) steam. To satisfy the MP steam needs of the compressor as well as the LP steam needs of the stripper column reboilers in an efficient manner the steam path was designed as shown in Figure 7.1 above. The auxiliary boiler will produce MP steam that will initially be supplied to the CO_2 compressor. After being utilized for compression, the MP steam is reduced to LP steam. This LP steam will then continue on to the CO_2 capture process and enter the stripper column reboilers to provide the required amine regeneration energy. The steam is condensed in the reboilers and exits as condensate.

7.2 Auxiliary Boiler Design

7.2.1 Process Description

A process flow diagram of the steam supply system is shown in Figure 7.2 below. The condensate from the reboilers is pumped by the CCS steam condensate return pumps to the auxiliary boiler deaerator. Two 100% Feed Pumps draw deaerated condensate from the deaerator and pump it as boiler feed water through to the auxiliary boiler.

The MP steam produced by the auxiliary boiler is then routed to the steam turbine driving the CO_2 compressor, after which it passes into the LP steam system. Excess MP steam not needed to drive the compressor is reduced in pressure and temperature at a quenching station before being fed into the LP steam system. LP steam is then fed to the CCS reboiler.

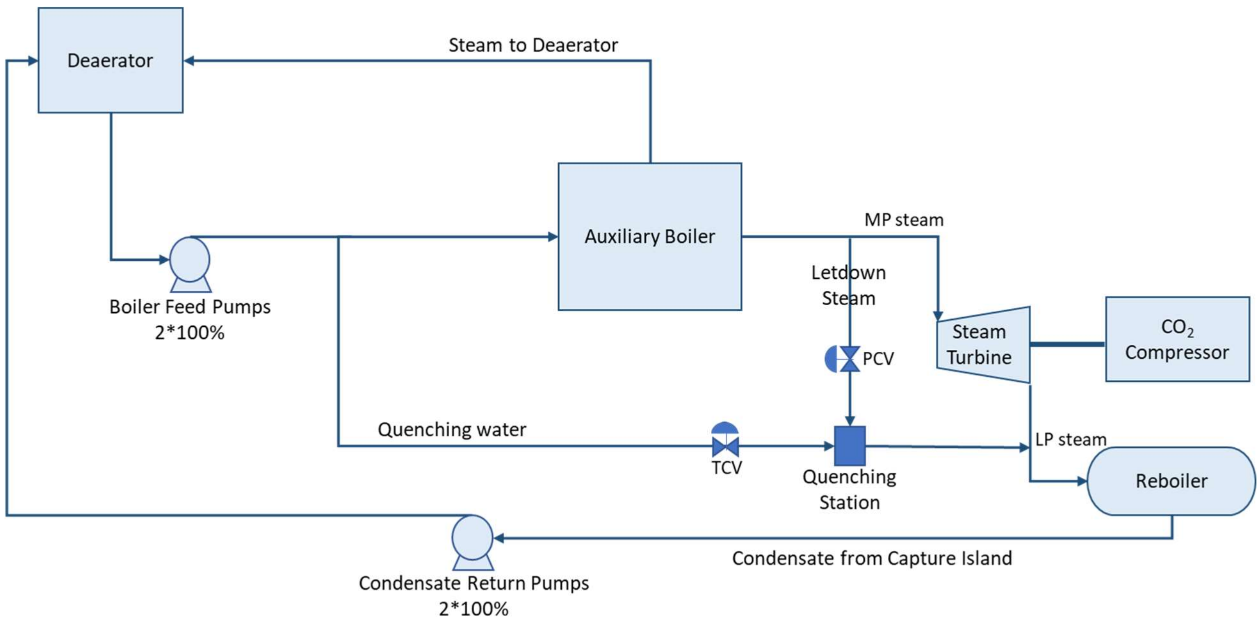


FIGURE 7.2 PROCESS FLOW DIAGRAM FOR STEAM SUPPLY SYSTEM

7.2.2 NO_X Emissions from the Auxiliary Boiler

The auxiliary boiler is expected to be able to achieve 16 g/GJi of NO_X emissions through the use of low-NO_X burners. Depending on the boiler manufacturer selected, flue gas recirculation (FGR) may or may not be required to achieve this NO_X emissions performance. NO_X formation in this boiler, operating at 15% excess air, is expected to be produced predominantly through the thermal NO_X mechanism. Typical rates of NO_2 formation for natural gas boilers is approximately 5% of the total NO_X (the remaining 95% being NO), this boiler is expected to produce NO_X species in line with this typical range.

7.3 Waste Heat Recovery (WHR)

The WHR system was designed to reduce the load on the auxiliary boiler. Operation of the WHR system is not required for the CO_2 capture plant to operate at design conditions. Figure 7.3 shows a simplified diagram of the steam supply system. If a WHR system is installed and produces steam to supply the CO_2 capture and compression process, the CO_2 compressor would be driven by a dual pressure admission steam turbine. The steam produced from the WHR system would enter at the later stage of the turbine as admission steam. When the WHR system is out of service, the turbine could be operated at full load without admission steam. However, further investigation is required during the detailed engineering phase.

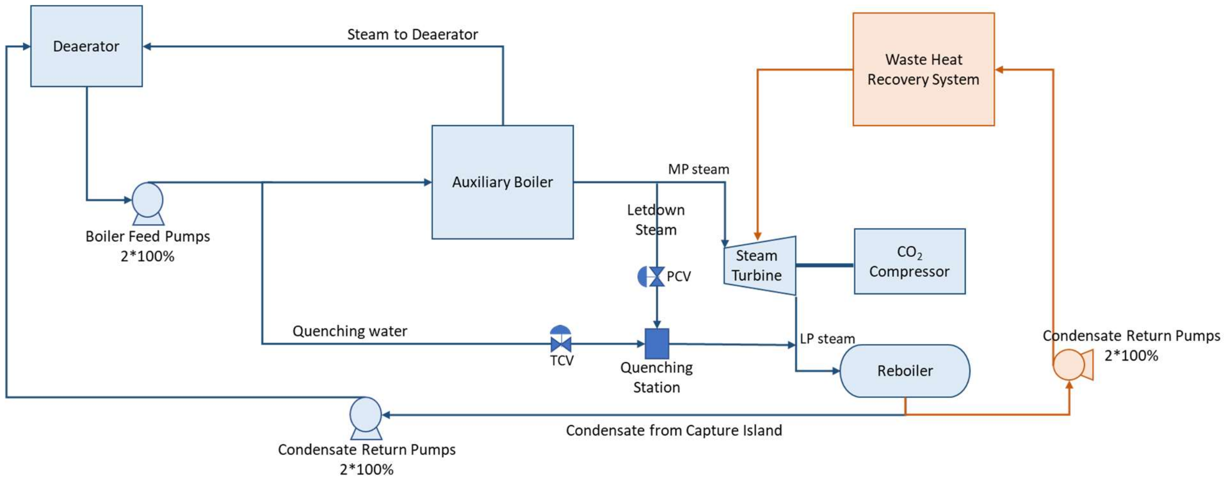


FIGURE 7.3 SIMPLIFIED DIAGRAM OF STEAM SUPPLY SYSTEM

7.3.1 Waste Heat Recovery Design Criteria

The following criteria would be the basis of the WHR system's design:

- Installation of the WHR boiler shall avoid increasing the heat consumption of the cement production line.
- Operation of the WHR boiler shall avoid altering normal cement production.
- The system design shall be mature, reliable, and have high availability with simple operation and maintenance.

7.3.1.1 Waste Heat Resources

Potential waste heat sources within the Lehigh facility were identified, quantified and assessed. Two sources were identified as having the potential to provide useful energy for the CCS process:

- the flue gas exiting the preheater tower; and,
- the clinker cooling air.

Both the flue gas exiting the preheater tower and the clinker cooling air are available on a continuous basis. At normal operating conditions, the flue gas exiting the preheater tower would be fed to the conditioning tower and would be cooled by water spray. The hot air from clinker cooler would also be fed to a cooler, reducing its temperature before entering the bag house.

TABLE 7.1 SUMMARY OF THE FLUE GAS EXITING THE PREHEATER TOWER AND CLINKER COOLER AIR PROPERTIES

	Unit	Cooler Exhaust	Preheater Outlet
Gas Flow	Nm^3/h	221,772	208,062
Gas Temperature	°C	260	417
Gas Composition			
CO_2	%vol	-	22.9
O_2	%vol	20.9	1.8
N_2+Ar	%vol	79.1	60.1
H_2O	%vol	-	15.1

Dust Loading	g/Nm^3	28.85	19.5

7.3.1.2 Thermodynamic System and Parameters of Steam Pressure

The WHR units were designed to provide steam with the conditions stated in Table 7.2.

TABLE 7.2 STEAM CONDITION FROM WASTE HEAT RECOVERY UNIT

	Unit	Parameters
Steam Pressure	bar abs	20
Steam Temperature	°C	300
Feed Water Temperature	°C	150

7.3.1.3 Different Working Conditions

The design of the WHR boilers was based on normal operating conditions. However, the plant can operate abnormally due to various factors. To account for abnormal operating conditions in designing the WHR boiler, the feasibility study investigated five operating cases including one normal and four abnormal operating conditions.

a. Case 1 – Normal Operations (Design case)

For the normal operating conditions case, the flue gas exiting a suspended preheater (SP) would be combined with any flue gas bypassing through the conditioning tower. This flue gas would pass through the ID fan and would be fed to a raw mill to dry raw material. The minimum temperature of the flue gas required for the raw mill at the normal operating condition is 268 ˚C.

b. Case 2 - Operations with high moisture feed

Annual feed stock data indicated that for approximately two months in an average year, the plant may be fed with high moisture raw material. During this time the raw mill requires a higher temperature flue gas (as measured at the inlet of the kiln ID fan), to dry the raw material. This would require the SP boiler to be operated with reduced heat recovery. A slip stream of hot flue gas could be diverted from the SP boiler to provide the mixed flue gas outlet temperature of 317 ˚C at the kiln ID fan inlet.

c. Case 3 - Operations with raw mill out of service

Operation data indicated that the raw mill could be out of service for approximately 16-18 hours per week for maintenance. In this case, the design flue gas outlet temperature of 268 °C could cause damage to the bags in the baghouse. To protect the baghouse, a maximum temperature limit of 210 °C for the flue gas temperature to the ID fan would need to be set. This could require cooling a slip stream of flue gas through the conditioning tower.

d. Case 4 – Operations with the SP boiler out of service

This case considered normal operating conditions for the existing cement plant but assumed the SP boiler to be out of service.

e. Case 5 – Operations with the clinker air quench cooler (AQC) boiler out of service

This case considered normal operating conditions for the existing cement plant but assumed the AQC boiler is out of service.

7.3.2 System Description

The WHR system was designed by Sinoma Energy Conservation Limited. To recover heat from the flue gas exiting the preheater tower and clinker cooler air, two different types of boilers, one to recover heat from each of the waste heat sources, would be needed (See Figure 7.4). An SP boiler would be utilized to recover heat from the portion of the flue gas from the preheater flue gas while an AQC boiler would be used to recover heat from the clinker cooler air. These two boilers would function together to produce steam which would then be fed to the required areas of the CO_2 capture and compression process. To ensure boiler failure would not affect cement production, each waste heat boiler would be equipped with bypass gas ducting. In the case of waste heat failure, the waste heat boilers can be isolated and removed from the cement production system without hindering normal cement production operations.

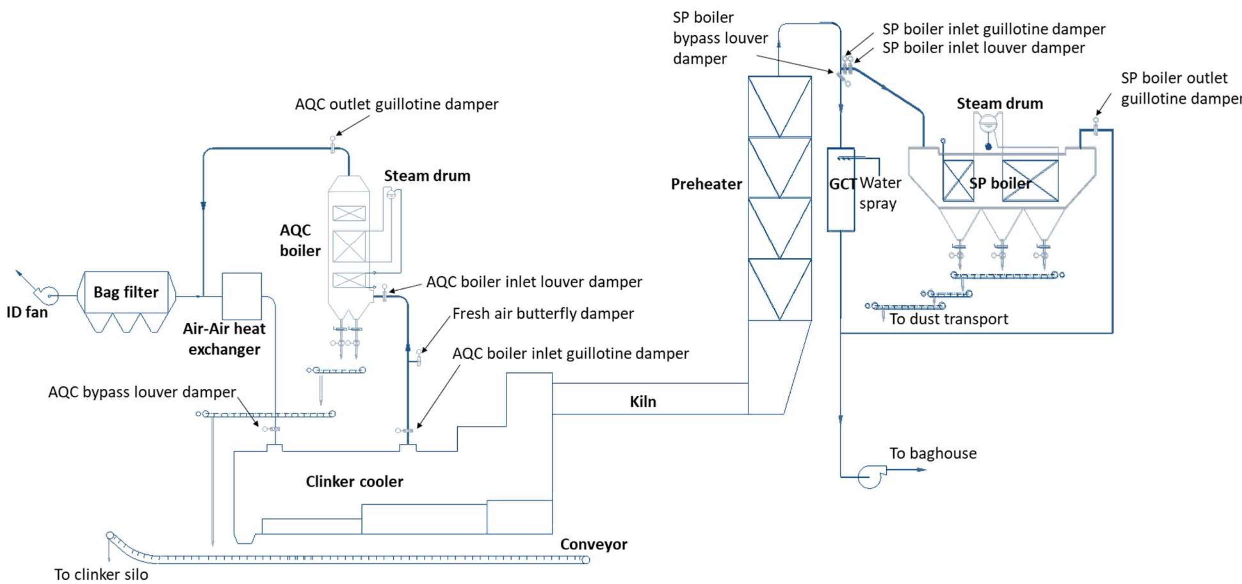


FIGURE 7.4 FLOW DIAGRAM OF WASTE HEAT RECOVERY SYSTEM (GAS)

When both boilers are in service, condensate from the CCS plant would be fed to a deaerator. Boiler feed pumps would be used to drive the condensate to the AQC boiler which would function as an economizer to preheat the condensate. Some of the preheated condensate would be fed to the bottom of the AQC boiler to generate steam. The remaining condensate would be sent to the SP boiler. Steam generated from both boilers would be combined and sent to the CO_2 capture plant for CO_2 compressing and solvent regeneration needs (See Figure 7.5).

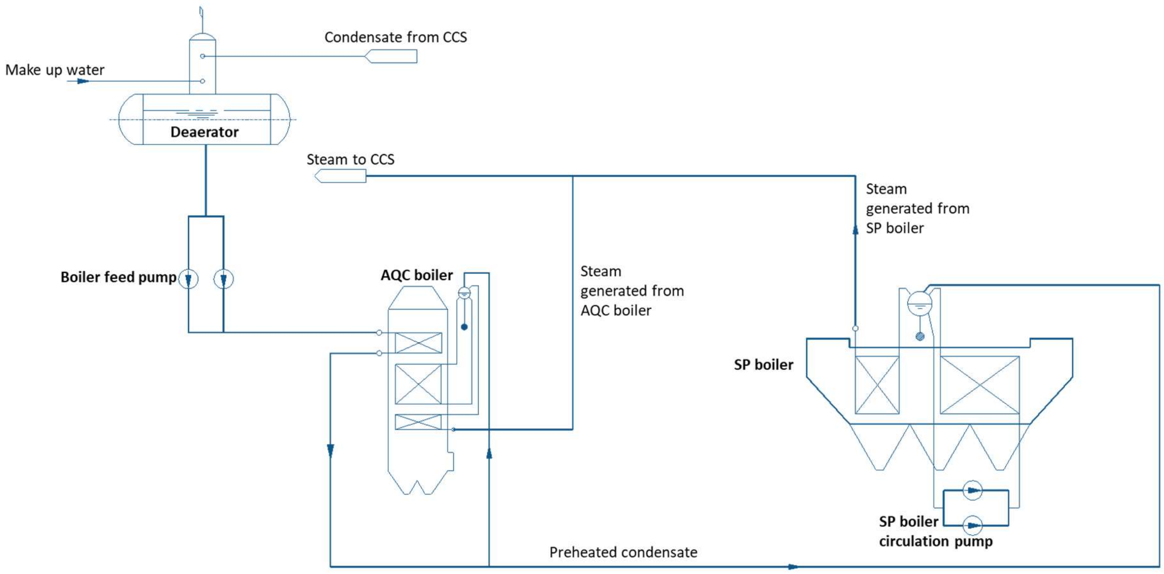


FIGURE 7.5 FLOW DIAGRAM OF WASTE HEAT RECOVERY SYSTEM (WASTE AND STEAM)

7.3.2.1 Air Quench Cooler Boiler (AQC Boiler)

To maximize utilization of heat from the cooler, a new hole will be opened on the middle stage of the cooler to access higher temperature hot air. The remaining gas will be exhausted through the existing cooler vent duct if necessary.

The AQC boiler is a vertical gas flow boiler with horizontal tubes. It is a natural circulation boiler with a drum. The vertical design reduces the footprint of the boiler, while also reducing air-leakage and increases the heat recovery rate. The large grain size of particulates at the outlet of kiln requires a precipitation chamber to be installed at the AQC boiler's bottom. This chamber facilitates the settling of the large particulates which reduces the scouring and wearing of the boiler. Modular design would be utilized for this boiler to reduce site installation and erection time.

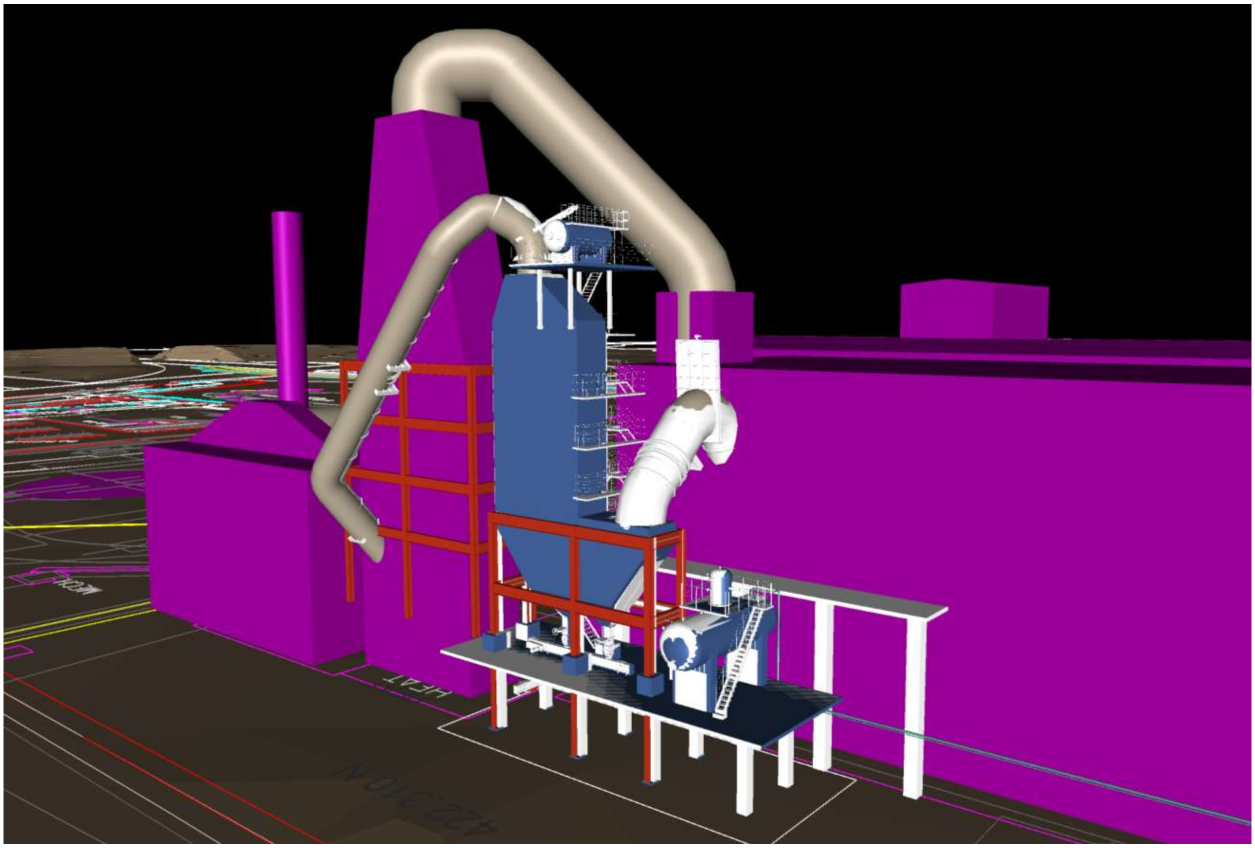


FIGURE 7.6 3D MODEL AQC BOILER

7.3.2.2 Suspend Preheater Boiler (SP Boiler)

Flue gas from the preheater tower enters the SP boiler where it would contact the heat exchanger surface to generate steam. After passing through the heat exchanger the gas would return to the existing duct upstream of the ID fan. The horizontal membrane type SP boiler utilizes forced circulation with a drum. A mechanical rapping system is also installed below the boiler for dust removal.

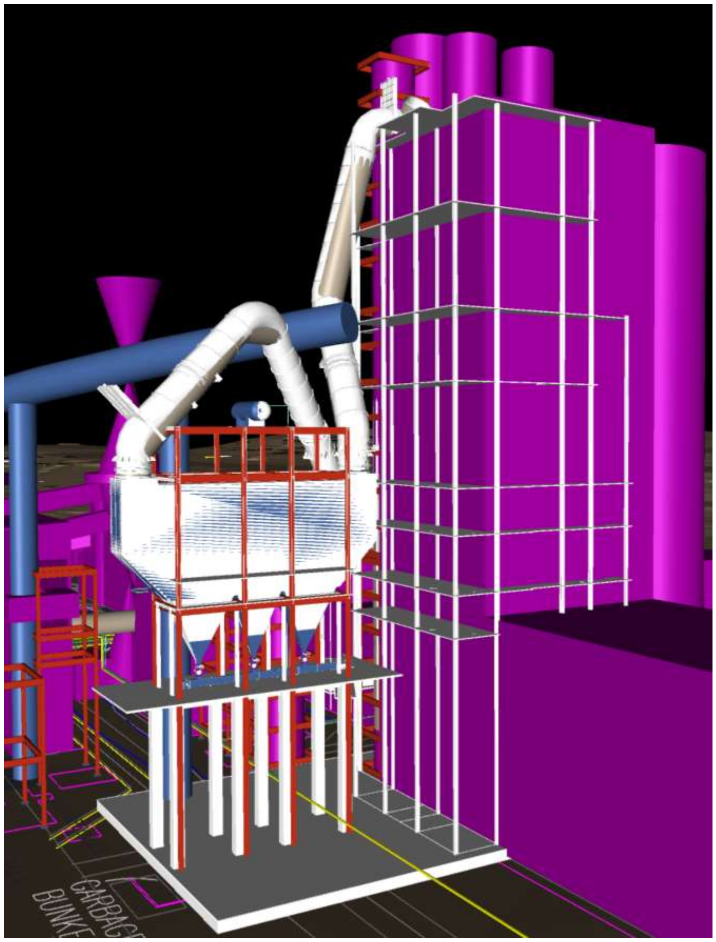


FIGURE 7.7 3D MODEL SP BOILER

7.3.3 Performance

At different operating conditions, the WHR boilers generate different amounts of steam. Figure 7.8 illustrates the required auxiliary boiler load with the different WHR system operating conditions. With heat recovery from the two hot gas streams in the existing plant and with normal operating conditions, the steam requirement from the auxiliary boiler can be reduced and the auxiliary boiler can be operated at only 85% load. This leads to a significant reduction in the fuel consumption for the auxiliary boiler. However, when the plant operates at abnormal conditions or if any of the WHR system is out of service, the performance of the WHR system can be significantly reduced. In the case of the SP boiler being out of service, the auxiliary boiler would need to be operated at 95% load.

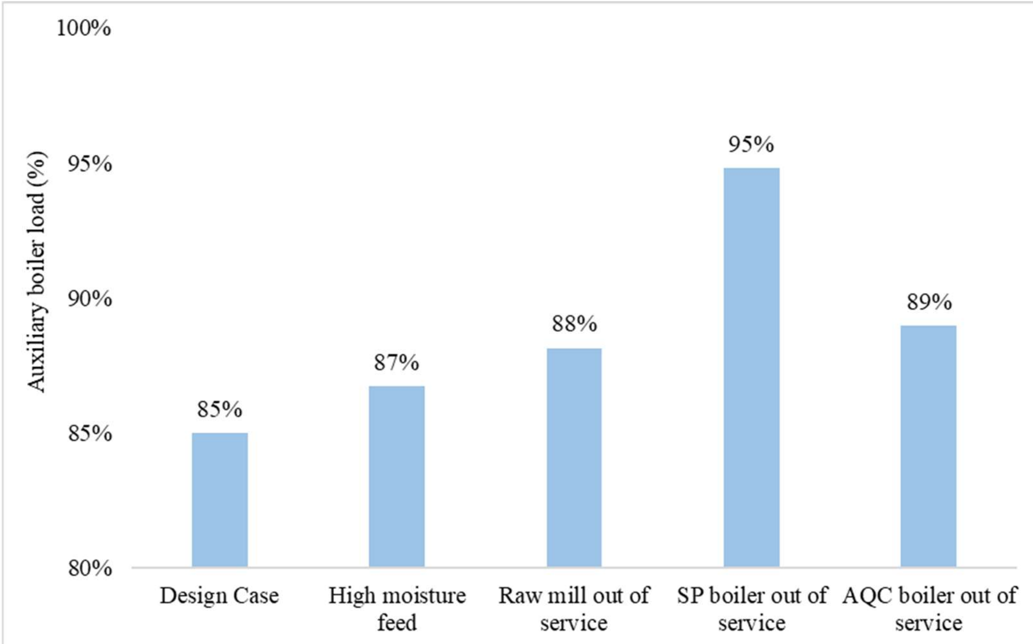


FIGURE 7.8 AUXILIARY BOILER LOAD AT DIFFERENT WASTE HEAT RECOVERY SYSTEM OPERATING CONDITIONS

7.4 Economic Evaluation and Recommendation

To determine whether the waste heat recovery system was economically justified, capital and operating costs and savings were developed. The operation of the two WHR units result in reduced steam demand and natural gas consumption of the auxiliary boiler. Table 7.3 summarizes the natural gas heat input with and without the WHR units.

TABLE 7.3 NATURAL GAS CONSUMPTION AND CO_2 EMISSION FROM THE AUXILIARY BOILER

Parameter	Auxiliary Boiler without WHRUs	Auxiliary Boiler with WHRUs
Heat Input, GJ/h (HHV)	478.4	407.7
Heat Input, kW thermal (HHV)	132,889.0	113,236.4
Exhaust Flue Gas Flow Rate, mt/h	181.4	154.5
CO_2 Flow rate, kg/h	24,226.3	20,643.5

The addition of the WHR units results in lower natural gas consumption and CO_2 emissions from the auxiliary boiler. The reduction in CO_2 emissions is 3582.8 kg/h or 21,969 mt/year. The net present value of the annual natural gas savings of $1,667,181 is $20,270,267. However, the saving from natural gas costs would be offset by the operations and maintenance requirements for the WHR units. Moreover, the indicative cost of the two WHR units including installation is $69,162,500. Therefore, installation of the WHR units is not economically feasible.

Chapter 8 Other Balance of Plant

This chapter describes the other BOP utilities and environmental impacts for the two site options selected during the desktop siting study. These include the pond option and the west of 170 option. The other BOP systems include the following:

- Utility systems which provide natural gas, compressed air, utility water, potable water, and demineralized water to the facilities.
- Utility bridge and piping
- Water treatment and waste management
- Other miscellaneous items such as sampling system, fire protection, sanitary drains
- Pond transfer (only applies to the pond option)

The pond transfer system is specifically applied to pond option only. It transfers water from the modified existing pond to the new pond located west of 170th Street. All other systems are technically identical between the pond option and the west of 170 option. The supporting systems for the WHR units were included as an option in this chapter, but the costs were excluded from the project cost estimate, because the study in the heat integration chapter concluded that WHR units are not economically feasible.

8.1 Approach and Design Basis

The systems were designed based on the assumption that there is no available capacity in the existing plant for utility services. This means equipment shall be installed separately from the existing plant to fully support CCS operations.

8.2 Utilities

8.2.1 Natural Gas Supply

Natural gas delivery is required to the auxiliary boiler and building enclosures for heating. Natural gas will be supplied via a tie-in point from the local utility. The tie-in pressure will be stepped down at the regulating skid. The natural gas will then be passed through a knockout drum to allow liquids and condensate to fall out of the stream ahead of combustion in auxiliary boiler and HVAC systems, thus protecting and prolonging the life of downstream equipment.

8.2.2 Compressed Air

This system is designed to supply clean, instrument quality, compressed air to equipment users around the plant. Some users include but are not limited to control valves, pneumatically actuated equipment, and instrumentation. Air from air compressors (air-cooled) is transferred and passed through a pair of air receivers/dryers. The dry air is then transferred to two air receivers where compressed air can then be piped to various users.

8.2.3 Service Water

A line connecting to the service water tie-in runs to a service water tank. Service water forwarding pumps pump water from the service water tank to the CCS system and various BOP utility stations throughout the plant. The header and pumps for service water are sized based on the maximum CO_2 capture plant flow requirement and three additional new utility stations running at once.

8.2.4 Potable Water

This system is designed to supply drinking quality water to the administration and emergency safety showers/eyewash stations throughout the plant. Potable water will tie into the existing system and supply water to the restroom enclosures. A branch will lead to a loop containing the potable water tempering skid. Attached to the loop will be two branches, one going to the CO_2 capture plant and the other going to BOP safety shower/eye wash loop. There are to be three emergency shower/eye wash stations within the main water treatment building, and one in the WSAC water treatment building.

8.2.5 Demineralized Water

Demineralized quality water is required for the CO_2 capture plant, deaerator make-up, and various flush processes. Two treatment options for this are listed below.

- Permanent Reverse Osmosis (RO) Option

The first option will reduce the frequency of offsite regeneration for the demineralizer trailers at the cost of installing the permanent RO skids.

- Demineralizer Trailer Option

The second option will only use demineralizer trailers and no RO skids, with a tradeoff of the regeneration frequency for the demineralizer trailers being required every week.

Comparing the two options, it was recommended to use demineralization trailers in order to avoid generating a waste stream that would have to be treated further, sent off-site to waste, or repurposed by the existing Lehigh Cement facility. Figure 8.1 is a process flow diagram of the demineralized water supply system.

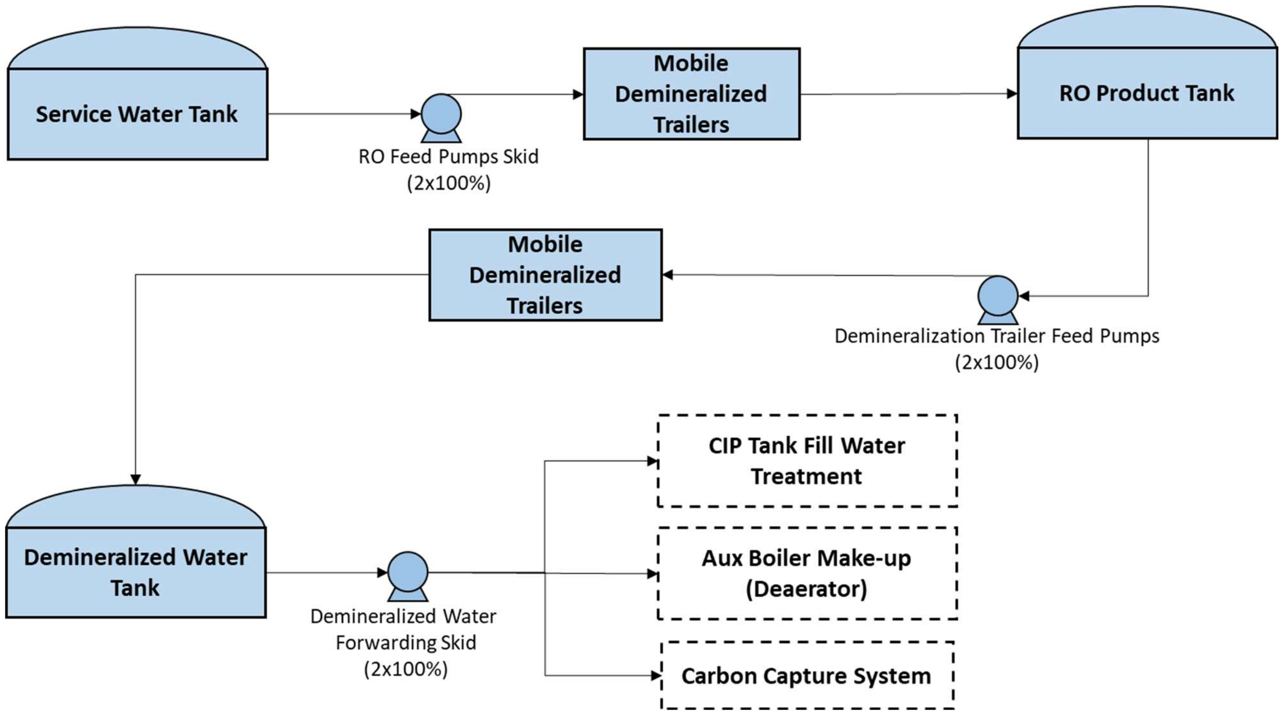


FIGURE 8.1 DEMINERALIZED WATER FLOW DIAGRAM

8.3 Utility Bridge and Piping

The design of the utility bridge utilizes a single level braced frame configuration to support the piping running from the BOP area to CCS area. The utility bridge supports multiple small-bore pipes and supports these pipes as they cross over a new road to get to the CO_2 capture plant. The utility bridge is designed to be wide enough to allow access along with the piping for maintenance and egress of the structure.

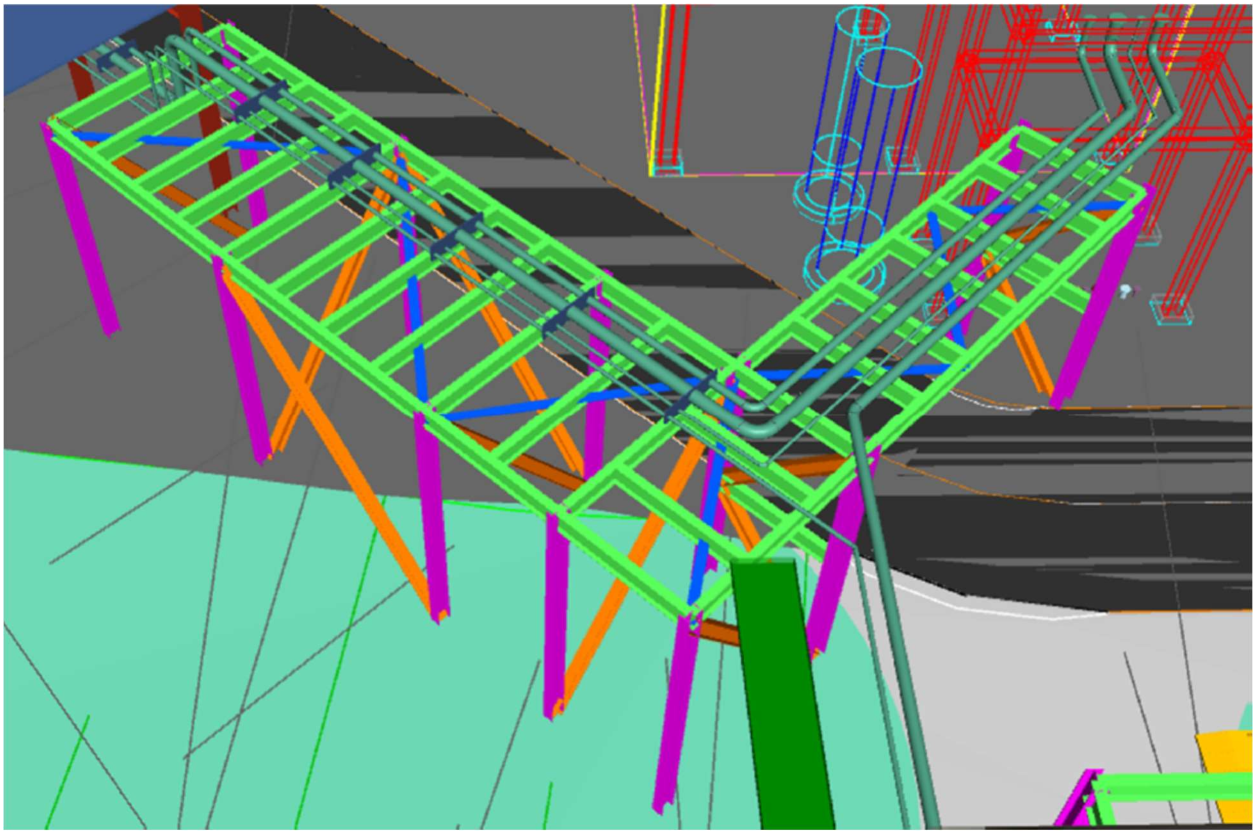


FIGURE 8.2 UTILITY BRIDGE

8.4 Flue Gas Condensate Water Treatment

Figure 8.3 is a process flow diagram for the water treatment plant that should be referenced for the following description.

Flue gas condensate is captured in a condensate storage tank. In order to be reused, the flue gas condensate must first be treated by an ultrafilter. Ultrafiltration pumps forward water through the flue gas condensate cooler to the filters. The flue gas condensate make-up water may be up to 54°C, and the water must be cooled so that it does not damage the ultra-filter membranes. After passing through the ultra-filters, the filtered water is stored in the filtered water storage tank. WSAC pretreatment forwarding pumps transfer the filtered water of permissible quality to the WSAC. If the raw mill is off, the water quality of flue gas condensate stream will exhibit much more total dissolved solids (TDS) in the form of SO_3/SO_4 and Na. This water will require further deionization using the RO skid to meet WSAC water chemistry requirements.

The ultrafilters will occasionally need to be cleaned through a backwash cycle if buildup occurs on the filters. In order to maximize the WSAC performance, the backwash will be sent to water recovery equipment and recycled to the front of the ultrafilters.

Alternatively, the backwash water could be sent to the cement plant while eliminating the need for the water recovery equipment which would save on the capital cost of the installed system. However, this water would not be available for WSAC makeup, therefore limiting the WSAC performance capability.

The ultrafilters will need to be chemically cleaned about once a month. They will be flushed via a clean in place (CIP) tank that will be filled with demineralized quality water. The CIP operation is used to periodically clean membrane systems in water treatment applications. Typically, high and low pH treatments are performed in stages per each cleaning.

An important aspect of these cleanings is proper heating of the solution for maximum effectiveness. In warm weather climates, only minimal heating of the cleaning solutions may be necessary to raise them to proper cleaning temperatures. This can be achieved depending on the water treatment building's ambient temperature inside the building. CIP wastewater is often removed from the site directly from the CIP skid via a vacuum truck or waste tote. Recycling CIP waste to the WSAC or other destination requires careful consideration due to wastewater discharge limitations.

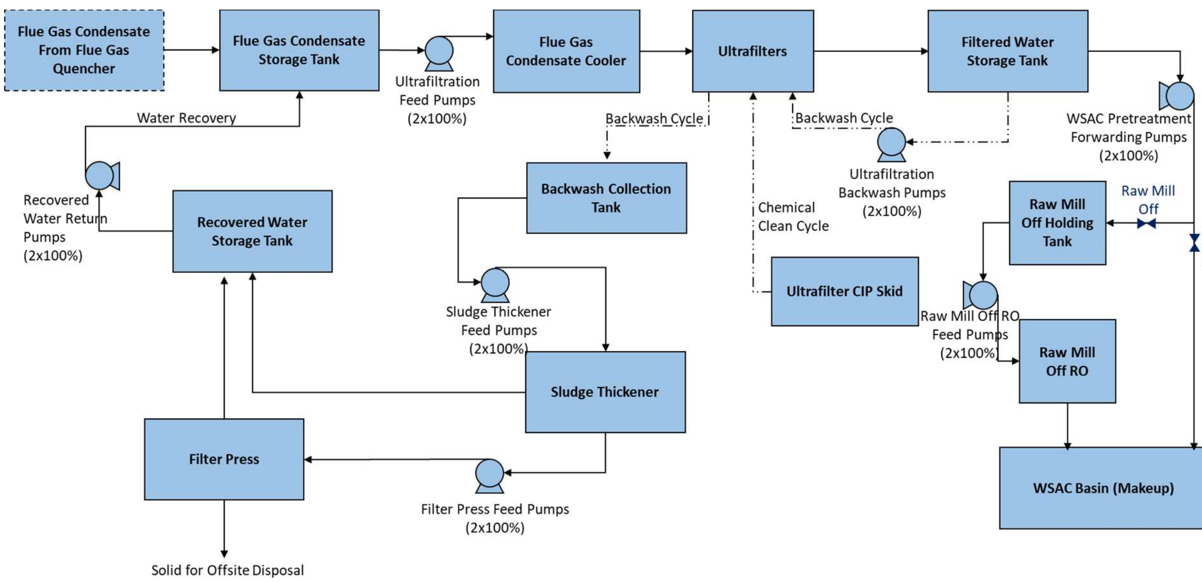


FIGURE 8.3 PROCESS FLOW DIAGRAM FOR WATER TREATMENT PLANT

8.5 Waste Management

The primary waste streams, their sources, and the methods of disposal are shown in Table 8.1. Wastewater process flow diagram is shown in Figure 8.4.

TABLE 8.1 SUMMARY OF WASTE PRODUCED AND PROPOSED DISPOSAL METHODS

Waste Stream	Disposal Method
TEG Waste	Collected in fracture tank and transferred offsite
Sanitary Drainage	Tie into sanitary system
Reclaimed Waste	Collected in waste tank and transferred offsite by vacuum truck
Laboratory Drainage	Stored in chemical waste pit and transferred offsite
Auxiliary Boiler Blowdown	Directed to finish mill water injection and conditioning tower water spray
WSAC Blowdown	Directed to finish mill water injection and conditioning tower water spray
Reverse Osmosis Skid Reject	Directed to finish mill water injection and conditioning tower water spray
Plant Drains	Directed to finish mill water injection and conditioning tower water spray
UF Chemical Waste Collection Tank	Collected in waste tank and transferred offsite by vacuum truck
Filter Press Solids	Collected in waste bin and transferred offsite
Oil Water Separator	Oil collection reservoir transferred offsite by vacuum truck
Fuel Gas Drains Tank	Hydrocarbons collected and transferred offsite by vacuum truck
WHRU Blowdown	Directed to WSAC basin. Alternatively, directed to finish mill water injection and conditioning tower water spray.

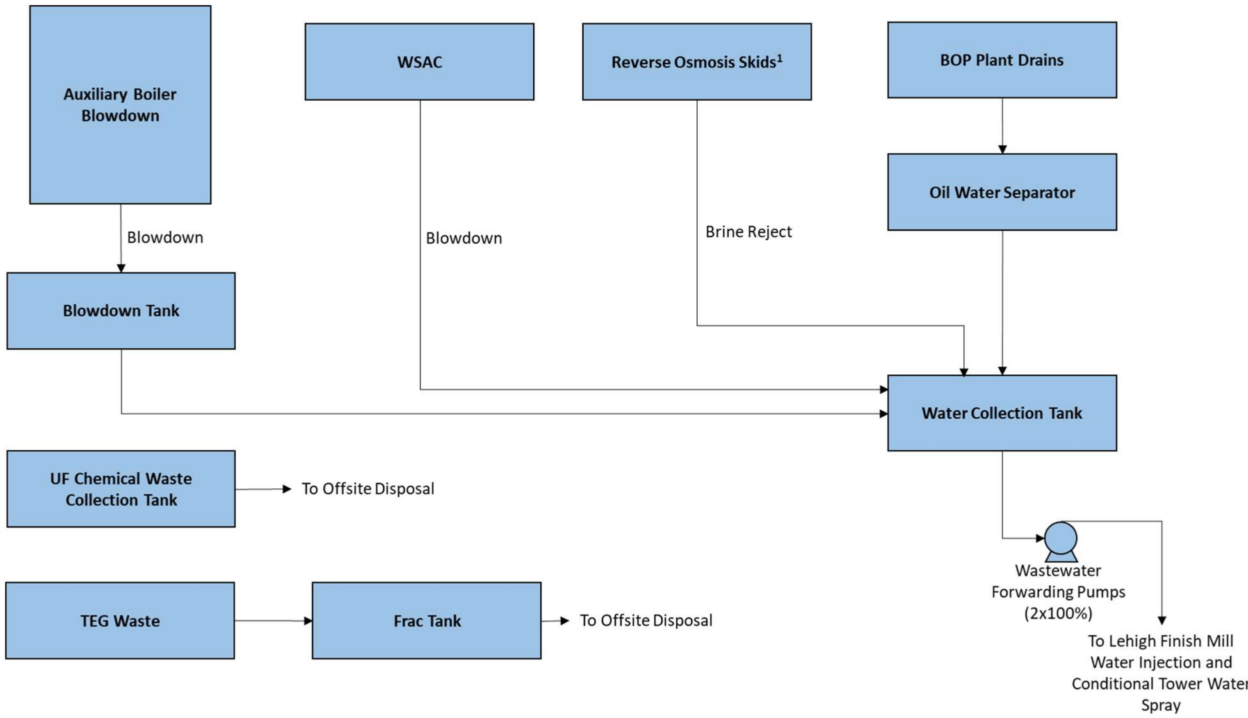


FIGURE 8.4 WASTEWATER PROCESS FLOW DIAGRAM

8.6 Other Miscellaneous

8.6.1 Chemical Feed

BOP Chemical totes and tanks will be located in a separate building from the CO_2 capture plant chemical totes and tanks. All piping will be run above ground. Suction lines are to be kept to minimal lengths. All pump skids will need to either be self-contained or have a containment foundation in the event of a spill, this is traditionally sized for 110% of the tote/tank volume. All chemical storage totes are to be kept inside a heated building. The chemical storage sizes vary based on their demand flow rate, ranging from a minimum tote size of 380 liters to maximum totes size of 1,500 liters to allow at least a minimum of 2 weeks between fillings.

8.6.2 Fire protection

The existing cement plant fire protection system is fed from a single storage tank. The tank is fed by the process water line and by the city, with associated pumps to fill the tank. There are no fire pumps, so any fire water usage relies on the water level in the tank unless it is boosted by the responding fire department trucks when they draw from the hydrants attached to the system. There are manual bypass lines to acquire water directly from the city, but the flow and pressures will need to be verified at this point.

The CO_2 compressor uses a lube oil console. It is expected that the lube oil console for the CO_2 compressor will be located indoors and will drive the need for a fire suppression system suitable for the situation. A fire water reserve storage should be established at the plant per code requirements and fire water pumps will be needed to provide sufficient firewater pressure. The new service water storage tank has been sized to account for this firewater reserve storage.

8.6.3 Sampling System

The sampling system will extract samples from selected points in the steam and water systems for analysis to inform adjustments to the operating procedures in order to minimize equipment corrosion and scaling. All piping shall be stainless steel tubing and run above ground. All lines shall have slope and an allowance for thermal movement with any sections of lines subject to freezing to be heat traced and insulated.

The Sample Panel contains a single direct line from the following samples:

- demineralized water - specific conductivity
- steam condensate pump discharge - pH, specific conductivity, and cation conductivity
- boiler feed pump discharge - pH, specific conductivity, and dissolved oxygen
- auxiliary boiler - pH, specific conductivity, and cation conductivity
- auxiliary boiler steam discharge - cation conductivity and silica
- WSAC water – chlorine, pH and specific conductivity
- service water pump discharge - free available chlorine
- closed cooling loop pump discharge – solvent used in CCS, pH, conductivity

8.6.4 Freeze Protection

Above ground, outdoor piping for all water systems will be insulated and heat traced. Outdoor storage tanks should be equipped with heating elements and insulated to the extent necessary to prevent freezing.

8.6.5 Sanitary Drains

CO_2 capture plant restroom enclosures will drain into a sanitary lift station. The sanitary waste will then be forwarded through a dry valve vault to the sewage system.

8.7 Pond Transfer System

The pond option requires that the existing pond be moved to a location west of 170 to make space for the CCS system and BOP equipment. The existing pond, among other purposes, is a retention basin for storm water drainage from the landfill adjacent to the cement plant. This storm water would need to be sent to the new pond location west of 170. Two (2)x100% detention basin transfer pumps, located in the new detention basin east of 170, will transfer water to the new pond.

Two pump houses draw water from the existing pond that supplies water to cooling systems for the cement plant. The pump houses will draw water from the detention basin similar to as it was with the existing pond. The new pond west of 170 will be provided with pumps that will supply water to the detention basin when additional cooling water is needed or if the detention basin water needs to be cooled. The pumps will supply sufficient flow to match the existing pump house demands.

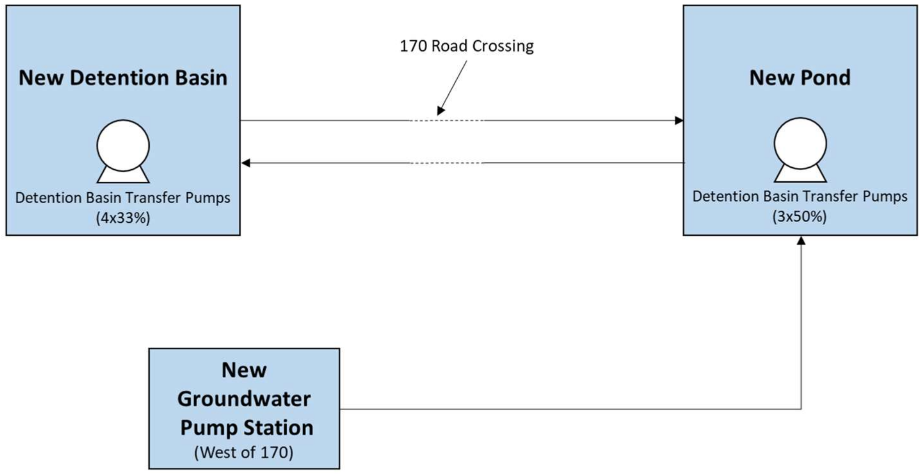


FIGURE 8.5 POND TRANSFER DIAGRAM

Chapter 9 Infrastructure and Civil Planning

This chapter summarizes infrastructure and civil planning for both pond option and west of 170 option. It presents site layouts which were optimized based on space available and constructability in each location. The site plans are intended to show proposed demolition, grading, drainage, roadway, and construction facility requirements for the CCS and BOP facilities. In addition, this chapter includes a study of the route that would be taken by the heavy haul transporters carrying equipment modules from the fabrication yard to the plant and an evaluation of the constructability of each option. The construction schedules for both sites are presented at the end of the chapter.

9.1 Pond Option A Site Plans

In the pond option the proposed equipment would be located in the footprint of the existing plant process water pond, requiring approximately 75 percent of it to be filled in. A replacement pond would be constructed on Lehigh property west of 170th Street, where the existing north pond is currently located. A detention basin and pump station would be provided in the remaining portion of the pond footprint to manage storm runoff that would still be routed to this location. The pump station would transfer stormwater to the relocated process pond west of 170th Street. Pumps at the relocated pond would supply water back to the detention pond via connections to the north and south pump houses. Figure 9.1 illustrates the site layout at the pond area.

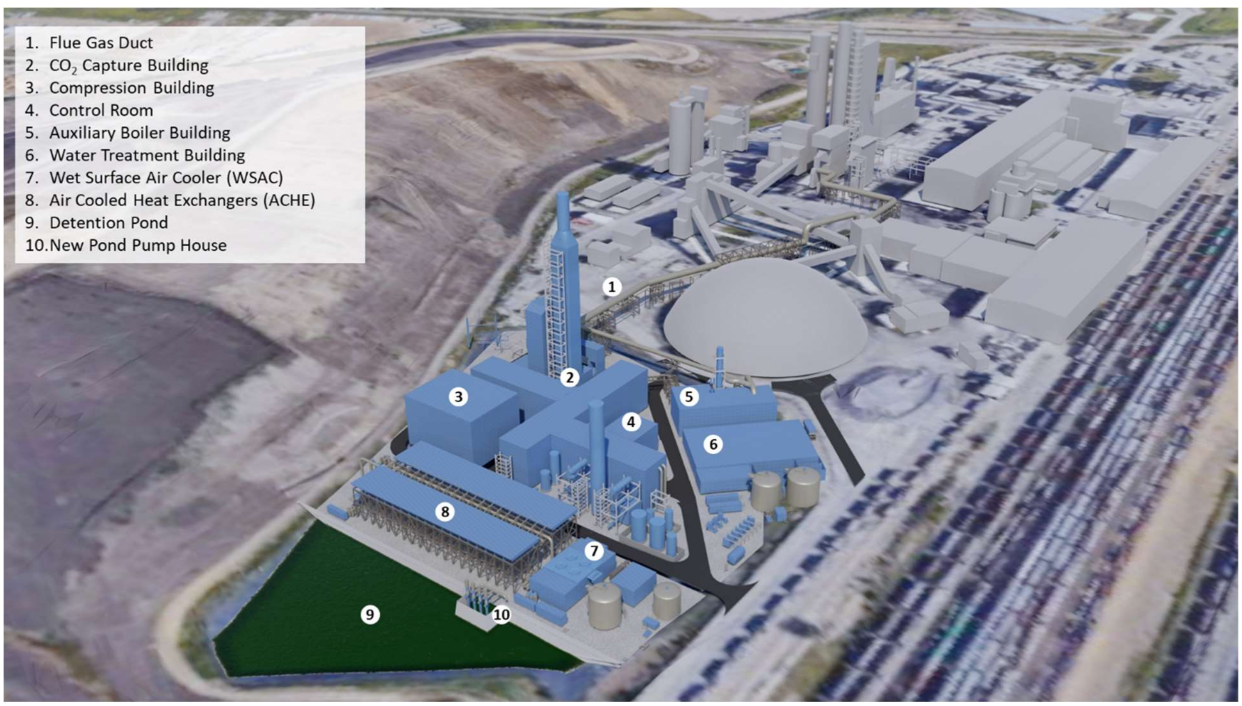


FIGURE 9.1 SITE LAYOUT FOR POND OPTION

9.2 West of 170 Option Site Plans

In the west of 170 option the proposed equipment would be located on the Lehigh property west of 170th Street. The existing process water pond would not be affected, and there would be no change to its operation. In this option, the flue gas duct would be routed from the cement plant to the CO_2 capture plant/BOP systems area along the existing haul road and cross under 170th Street. The layout of the CO_2 capture plant and BOP systems at the west of 170 location is illustrated in Figure 9.2.

FIGURE 9.2 WEST OF 170 LOCATION CCS AND BOP FACILITIES LAYOUT

9.3 Constructability

Space requirements during construction for crane placement and module staging have been evaluated for pond option A. The requirements for the west of 170 option are similar, but less restrictive since there is more room at that site. Two options have been identified for crane selection and erection sequence.

9.3.1 Crane Option 1

- Utilize a Liebherr 1750 without a ballast wagon due to the compact site plan and expected traffic through the site.
- Absorber module erection:
  - The absorber and quencher will need to be erected prior to starting erection of the duct and steel on the east side of the quencher but should be able to proceed with the fan.

- There is a fabrication area near the quencher/absorber fan area to allow some staging or final attachments to be made before lifting.

- Regenerator module erection:
    - Some of the ACHE sections will likely need to be left out until the lift is complete.

9.3.2 Crane Option 2

- Absorber module erection:
    - Uses a Liebherr LR 11350 in a SW2 boom configuration to keep the absorber box away from the boom.

- Regenerator module erection:
    - Instead of leaving ACHE sections out, an alternative would be to have the heavy haul company detail a "tilt up hinge" attached to the base of the regenerator and use a Goldhofer as the tailing mechanism.
    - Uses the same LR 11350 provided for the absorber module but adds a wagon and straight boom to stand off a bit and pick the regenerator.

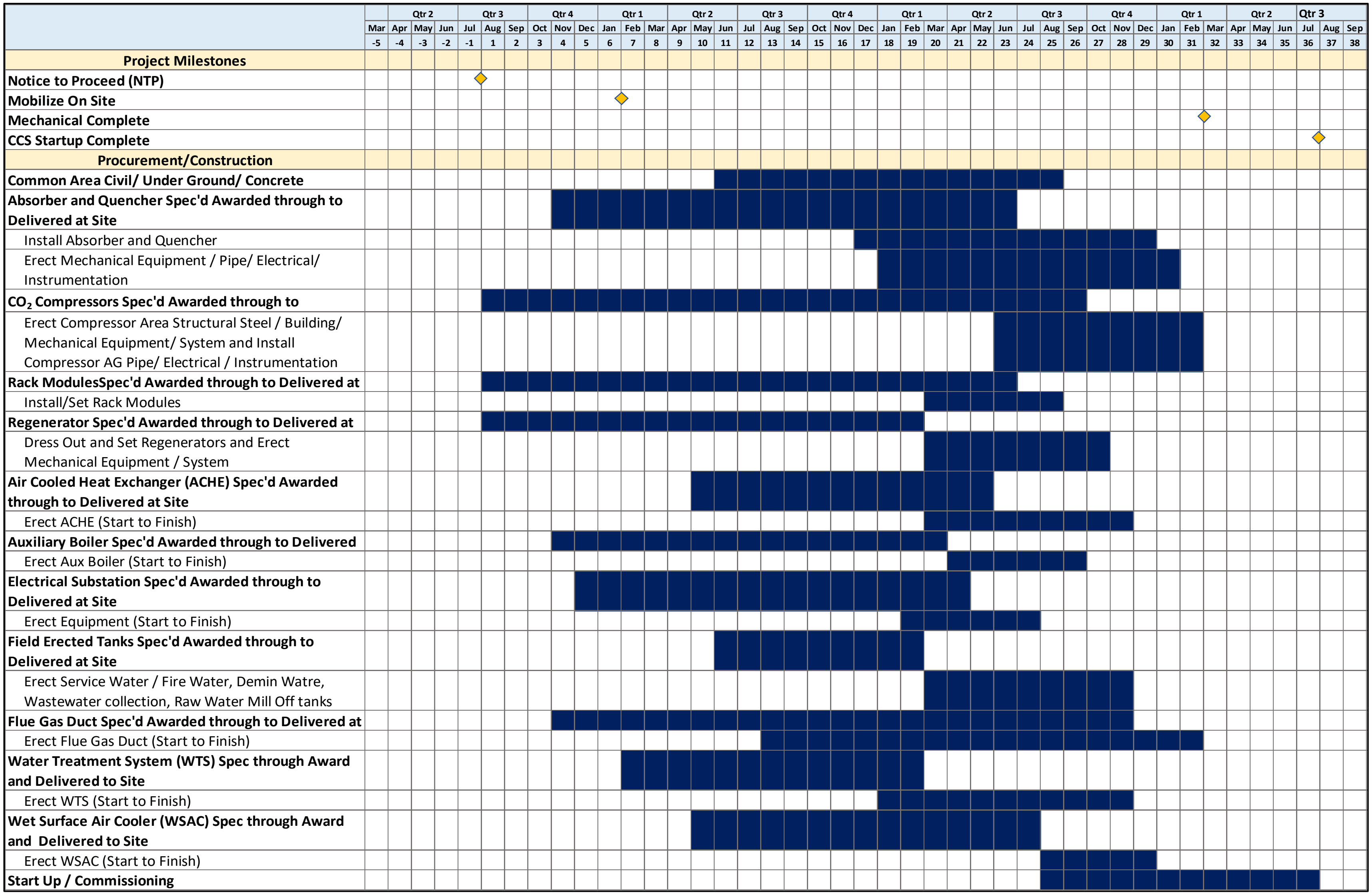
9.4 Construction Schedule

The Level 1 construction schedule for both pond area and west of 170 area are illustrated in Table 9.1 and Table 9.2. The Level 1 Schedule indicates that procurement, construction, and commissioning should be complete within 36 months for west of 170 area. For pond area, the construction is required to start five months earlier to accommodate the pond relocation.

TABLE 9.1 LEVEL 1 SCHEDULE FOR POND OPTION

		Qtr 2			Qtr 3			Qtr 4			Qtr 1			Qtr 2			Qtr 3			Qtr 4			Qtr 1			Qtr 2			Qtr 3			Qtr 4			Qtr 1			Qtr 2			Qtr 3		
	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
	-5	-4	-3	-2	-1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Project Milestones																																											
Notice to Proceed (NTP)						◆																																					
Mobilize On Site												◆																															
Mechanical Complete																																							◆				
CCS Startup Complete																																										◆	
Procurement/Construction																																											
Pond Relocation																																											
Excavate North Pond / Embankment / Install Liner	■	■	■	■	■	■	■	■																																			
Coffer Dam / Dewater / Install Pump Intake at				■	■	■	■	■																																			
Install Mec/Elec to North Pond / Existing						■	■	■																																			
Coffer Dam / Install Retaining Wall / Backfill at									■	■	■	■	■	■	■	■	■																										
Common Area Civil/ Under Ground/ Concrete																■	■	■	■	■	■	■	■	■	■	■	■	■	■	■													
Absorber and Quencher Spec'd Awarded through to									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■															
Install Absorber and Quencher																						■	■	■	■	■	■	■	■	■	■	■	■	■									
Erect Mechanical Equipment / Pipe/ Electrical/																							■	■	■	■	■	■	■	■	■	■	■	■	■								
CO_2 Compressors Spec'd Awarded through to Delivered at Site						■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■												
Erect Compressor Area Structural Steel / Building/ Mechanical Equipment/ System and Install																											■	■	■	■	■	■	■	■	■	■							
Rack ModulesSpec'd Awarded through to Delivered at						■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■															
Install/Set Rack Modules																									■	■	■	■	■	■													
Regenerator Spec'd Awarded through to Delivered at						■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■																			
Dress Out and Set Regenerators and Erect																									■	■	■	■	■	■	■	■											
Air Cooled Heat Exchanger (ACHE) Spec'd Awarded															■	■	■	■	■	■	■	■	■	■	■	■	■																
Erect ACHE (Start to Finish)																									■	■	■	■	■	■	■	■	■										
Auxiliary Boiler Spec'd Awarded through to Delivered									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■																		
Erect Aux Boiler (Start to Finish)																										■	■	■	■	■	■												
Electrical Substation Spec'd Awarded through to										■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■															
Erect Equipment (Start to Finish)																										■	■	■	■	■	■												
Field Erected Tanks Spec'd Awarded through to																			■	■	■	■	■	■	■	■	■																
Erect Service Water / Fire Water, Demin Watre, Wastewater collection, Raw Water Mill Off tanks																											■	■	■	■	■	■	■	■									
Flue Gas Duct Spec'd Awarded through to Delivered at													■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■										
Erect Flue Gas Duct (Start to Finish)																						■	■	■	■	■	■	■	■	■	■	■	■	■	■								
Water Treatment System (WTS) Spec through Award																	■	■	■	■	■	■	■	■	■	■	■	■	■														
Erect WTS (Start to Finish)																											■	■	■	■	■	■	■	■	■	■	■						
Wet Surface Air Cooler (WSAC) Spec through Award															■	■	■	■	■	■	■	■	■	■	■	■	■	■	■														
Erect WSAC (Start to Finish)																														■	■	■	■	■									
Start Up / Commissioning																																■	■	■	■	■	■	■	■	■	■		

TABLE 9.2 LEVEL 1 SCHEDULE FOR WEST OF 170



Chapter 10 Environmental and Permitting

This chapter presents a summary of an environmental review of the proposed three footprints and describes the regulatory requirements that may be required to permit the facility. The three footprints are:

- Option 1. Move the stormwater pond to the west of 170th Street NW and construct the CCS at the location of the existing stormwater pond
- Option 2. Move the stormwater pond to the north edge of property and construct the CCS at the location of the existing stormwater pond.
- Option 3. Construct the CCS west of 170th Street NW and retain the existing stormwater pond at the current location.

The environmental reviews included a Phase I environmental site assessment (ESA), an environmental permit matrix, and emission thresholds for amine and amine degradation products. In addition, early environmental modeling and site investigations are also presented. Three main footprints were observed to analyze potential and actual sources of contamination. The footprints included a 100-meter buffer surrounding the infrastructure locations.

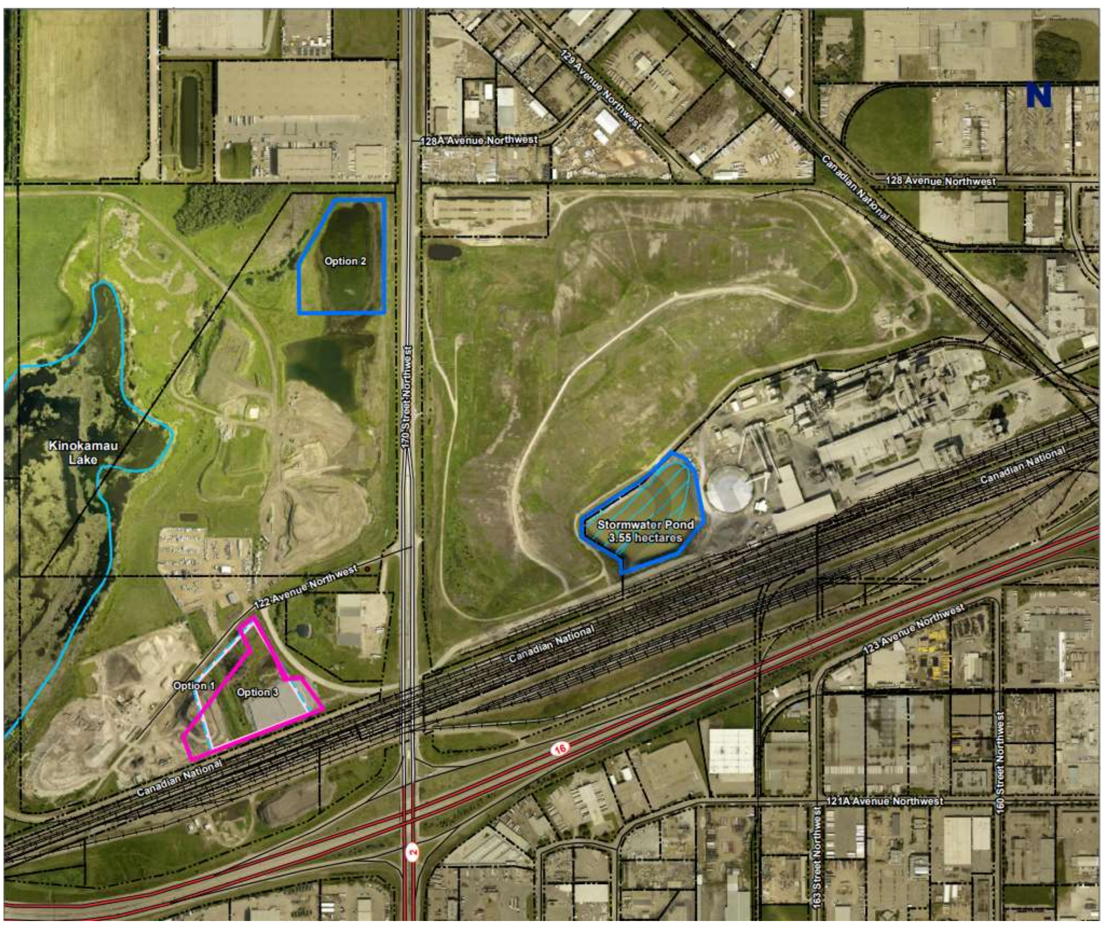


FIGURE 10.1 THE THREE FOOTPRINTS BEING CONSIDERED FOR ENVIRONMENTAL REVIEW

10.1 Phase I Environmental Site Assessment (ESA)

A limited Phase I ESA was conducted to identify actual and potential sources of soil and/or groundwater contamination that may be present in/near the assessment area. The Phase I ESA was conducted for three proposed CCS construction footprint options.

10.2 Environmental Permit Matrix

A permit matrix has been developed. Table 10.1 describes specific permits and risks known at this time. All of the permits below are applicable for all options, though varying risks are described.

Note*

Low Risk:	minimal uncertainty in obtaining permit and timeline associated.
Medium Risk:	some uncertainty in permitting process (unknowns with regulators at this time, that can be mitigated in the near future) with long lead times associated.
High Risk:	requires additional review and consideration, potentially significant permitting uncertainty, including compliance and/or long lead times.

TABLE 10.1 SPECIFIC PERMITS AND RISKS

Anticipated Permit	Risk Level	Risk Mitigation
Species at Risk Act	Low Risk	• Municipal approvals will determine future impact studies. May require field surveys for potential at risk species. Completing studies will mitigate risk and allow for strategy development.
Migratory Birds Convention Act	Low Risk	• Municipal approvals will determine future impact studies. May require field surveys for potential at risk species. Completing studies will mitigate risk and allow for strategy development.
Water Act	Potentially High Risk based on option selected	• EPEA approved stormwater management plan • Public consultation required with application • Five non-natural wetlands were identified within the options. Water Act application required for diversion of water to pond. • There is a natural wetland adjacent to Option 2 and the clay pit. During the desktop review, this area was identified as needing additional research to verify compliance with Water Act regulations. Lehigh has independently conducted an onsite wetlands review and the project is awaiting the final report.
Wildlife Act	Low Risk	• Municipal approvals will determine future impact studies. May require field surveys for potential at-risk species. Completing studies will mitigate risk and allow for strategy development.

Environmental Protection and Environment Act	Medium-High Risk	• Changes to the stormwater pond will require City of Edmonton approval (drainage plan) and AEP Water Act Permit. • Highly likely an amendment for CCS construction and operation will be requested by regulators. Air modelling may be required to complete this process. • CCS documentation and preparation time can result in long lead times and makes this a higher risk item. Discussions with engineer will mitigate risk and allow for strategy development.
EPCOR Drainage	Medium-High Risk	• Changes to the stormwater pond may require a Water Act permit (AEP) and drainage assessment and approval from the City of Edmonton (Sanitary will be EPCOR) including runoff plan (medium risk, pending option selected). Pending stormwater engineer approval adds some risk. Discussions with engineer to mitigate risk.
Environmental Site Assessment Guidebook	Medium Risk	• Phase II ESA is recommended to further understand areas of concern as addressed in phase I based on the selected footprint. Potential unknown risks at this time. Phase I and II ESA review period varies (3-6 months). Completing the phase II ESA will mitigate risk and allow for strategy development.
Biophysical Impact Assessment (BIA)	High Risk	• Once an option is selected, the level of detail and effort of BIA can be determined. Timeline for preparation and review can be upwards of 12-18 months due to survey season (May-October). At this time, this is a high risk item due to the unknown survey results and timeline.

10.3 Environmental Impact Assessment (EIA) Applicability

The Environmental Assessment (mandatory and exempted activities) Regulation was established on September 1, 1993, and requires an EIA for all mandatory listed activities as well as some discretionary activities. Exempt projects do not require an EIA. Terms or systems related to carbon capture technology are not listed as mandatory or exempt. Since direct guidance is not available within the regulation, engagement with the regulator will be required to determine if an EIA is required.

10.4 Desktop Air (Emissions) Assessment

Desktop air modeling was performed for the project based on emissions from the absorber and auxiliary boiler stacks. The analyses were separated into two categories; criteria pollutants and air toxics, including amine and ammonia. Criteria pollutants are emitted from both the absorber and the auxiliary boiler stack, so the combined impact of both sources was analyzed.

For the air toxics, amine and ammonia were modeled from the absorber only. The amine emission rate was also used as the emission rate for modeling additional contaminants with established Alberta

Ambient Air Quality Objectives (AAAQO) that are formed due to the release of amine into the atmosphere. The model results are acceptable and meet all Alberta requirements.

Generally, for all pollutants evaluated, the maximum predicted impacts were below their respective AAAQO, and thus the CO_2 capture plant as currently designed can be expected to not adversely affect the surrounding ambient air quality. Note however that this conclusion does not take into account any expected future ambient air limits for amine (or other amine related products) that will be set for the CCS.

10.5 Emission Threshold for Amine and Amine Degradation Products

The carbon capture process involves the introduction of an aqueous solution of amines to the flue gas from the cement manufacturing process. A portion of the amine solution is expected to be released into the atmosphere along with the cleaned flue gas. Once in the atmosphere, the amines can break down into several contaminants of concern, principally ammonia (NH_3), short-chain amines (methylamine and ethylamine), and aldehydes such as acetic acid, formaldehyde, and acetaldehyde. These contaminants are known to be environmentally hazardous, and many are regulated as such.

The Lehigh Cement Edmonton CCS project will result in enforceable volatile organic compound (VOC) regulations that will need to be addressed. Research from similar projects show that an Environmental Assessment may be required, although perhaps not at the level of an EIA. The nature of Lehigh's project having a lesser increase in criteria air pollutants compared to the Shell Quest CCS project may preclude the requirement of such an analysis. More likely requirements to be expected are recordkeeping and emissions testing for any VOC related equipment and storage, as well as demonstrations of compliance with the AAAQC using dispersion modeling. Looking ahead at the potential for more stringent VOC regulations, there do not appear to be any changes imminent in Alberta that would adversely affect the permitting and operation of the CCS facility at Lehigh Cement.

10.6 Contaminant Plan

The contaminant plan is designed to serve as an operational plan to support identification and management of contaminants (including priority contaminants) if such contaminants are encountered during construction activities. Specific emphasis is placed on potential risks identified in the Phase 1 Report. Since the specific project site is currently unknown, the information is a only high-level view. The document is intended to be revised and modified to fit the project needs as the project progresses and as details and scope are developed and available.

10.7 Cost Estimate

10.7.1 Additional Testing/ Field Investigations

The testing and field investigations listed below are recommended to inform the permitting process based on the risks identified in Table 10.2.

TABLE 10.2 ADDITIONAL TESTING AND FIELD INVESTIGATIONS

Risk	Option 1	Option 2	Option 3	Proposed Mitigation
Above-ground storage tanks	X	X	X	Conduct a Phase II ESA
Former underground storage tanks	X	X	X	
Asphalt plant Stockpiles	X		X	
Rail yard (off-site)	X	X	X	
Demolition of hazardous building materials	X	X	X	Review and utilize third party testing to identify hazardous building materials (e.g., asbestos and lead).

10.7.2 Obtaining Permits for Construction and Operation

Table 10.3 describes specific permits, requirements for next steps, additional associated studies/reports, and the costs to prepare them.

TABLE 10.3 PERMITS FOR CONSTRUCTION AND OPERATION OF THE CO_2 CAPTURE PLANT

Anticipated Permit	Risk Level	Risk Mitigation
Species at Risk Act	Low Risk	Conduct a reconnaissance level site investigation. Assumes limited habitat potential given the level of existing disturbance but will be addressed as part of the EPEA application.
Migratory Birds Convention Act	Low Risk	Conduct a reconnaissance level site investigation. Assumes construction activities will comply with timing restrictions for breeding birds.
Wildlife Act	Low Risk	Conduct a reconnaissance level site. Assumes limited habitat potential give the level of existing disturbance but wildlife habitat will be addressed as part of the EPEA application. Assumes construction activities will comply with legislation and not disturb wildlife nests, dens, etc.

As the Project may be located at Option 3 (west of 170), where there is natural vegetation and potential wildlife habitat, a one-day field assessment will be completed to support the desktop ecological components that will be required as part of the *Environmental Protection and Enhancement Act* (EPEA) application including vegetation, soils, wildlife, and landscape/land use context, which is currently zoned as DC2.

TABLE 10.4 PERMITS FOR CONSTRUCTION AND OPERATION OF THE CO_2 CAPTURE PLANT

Anticipated Permit	Risk Level
Water Act (WAA)	Potentially high risk based on option selected
Environmental Protection and Environment Act (EPEA)	Medium-High Risk
Environmental Site Assessment Guidebook	Medium Risk
Historical Resources Act	Low Risk

Environmental Protection and Enhancement Act **(EPEA) Amendment**

- Meet with AEP as required to verify the expectations on the amendment application content.
- Review pertinent past approval documentation.
- A desktop and field-based biophysical assessment, desktop hydrogeological assessment, and air quality assessment will be completed.
- A Historic Resource Clearance Application will be prepared and submitted.
- Develop a draft approval amendment application in accordance with the *Environmental Protection and Enhancement Act*: EPEA Guide to Content for Industrial Approvals Applications.
- Prepare the approval amendment application submission package.

Noise Assessment

The City of Edmonton Bylaw 14600 Community Standard prescribes daytime (7 AM to 10 PM) and nighttime (10 PM to 7 AM) noise level limits for residential and non-residential areas.

A preliminary noise assessment of the Project noise effect within the study area (a 1.5 km buffer from the Project) will be conducted during the FEED study phase of the project. The assessment will include the following tasks:

- Confirm CO_2 capture plant information and noise sources
- Complete noise assessment
- Prepare report

City of Edmonton Land Use Planning and Development

The current zoning for the proposed Project locations includes Industrial (IH) and various Direct Control 2 (DC2) zones. The DC2 539 and DC2 540 zones both include provisions for general industrial uses. The DC2 542 zone does allow for general industrial use but is more specific and describes permitted uses including fabrication, processing, and general contractor services. These zones are shown in the Edmonton Zoning Map Figure 10.2 below. Also shown on this map are the location options for both the Carbon Capture and Storage plant (CCS) and the storm Water Management Facility (SWMF).

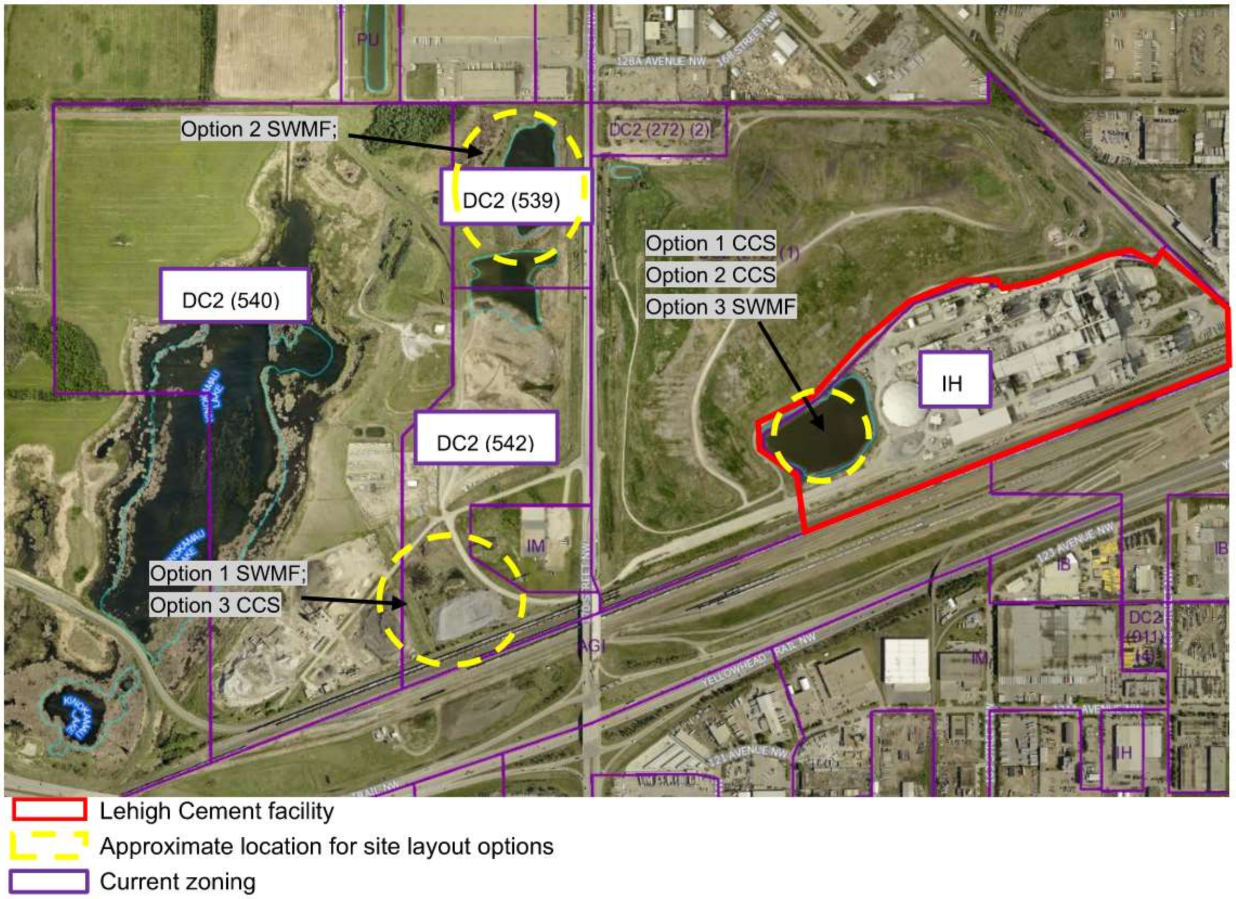


FIGURE 10.2 EDMONTON ZONING MAP

Other items to note include a conservation easement on the Kinokamau Lake Wetland with a 50 m setback from the line of emergent vegetation that prohibits direction of stormwater into the Kinokamau Lake Wetland. In addition, development applications adjacent to the Kinokamau Lake watershed will be referred to the Kinokamau Lake Management Committee by the City for comments prior to consideration for approval.

10.8 Conclusions and Recommendations

Overall, the project has completed all of the major goals identified in this work scope with the exception of a definitive decision on whether an EIA or another less stringent environmental review is required. Additional desktop and site investigation work will be required to identify all environmental and permitting risks associated with the proposed project. Final selection of the CO_2 capture plant footprint will be required to support development of permit applications and advanced coordination with regulators.

Chapter 11 Cost Estimates

This chapter summarizes the estimated capital, construction and operating costs for the addition of CO_2 capture and compression processes and the BOP systems required to support the CO_2 capture operation.

11.1 Capital Construction Costs

The capital construction cost estimate consists of two distinct components, the capture and compression systems, which was provided by MHI, and the BOP systems required to support and integrate the capture process, which was estimated by Kiewit (both overseen to completion by the Knowledge Centre). The capital construction cost estimate was developed to AACE Class 4 accuracy.

11.1.1 CO_2 Capture and Compression System Costs

The flue gas pretreatment, and CO_2 capture and compression systems, including all necessary equipment and buildings, were designed and costed by MHI. MHI produced an indicative EPC cost estimate for the capture and compression systems.

11.1.2 Balance of Plant Capital Cost

The BOP cost estimates developed by Kiewit were divided into eight main scopes including:

- Flue Gas Supply
- Heat Rejection
- Electrical and Instrumentation and Controls
- Utility Bridge
- Other Balance of Plant
- Infrastructure
- Environmental and Permitting
- Auxiliary Boiler

The capital cost breakdown for each BOP system for both the west of 170 and pond options are shown in Figure 11.1. These results illustrate that the additional costs associated with the longer duct and power costs for the west of 170 option were offset by additional earthwork associated with the pond option and the complexity involved in ensuring a water supply for the cement plant. Once these details were factored in to the Class 4 cost estimate, these two options ended up very similar in terms of the overall cost.

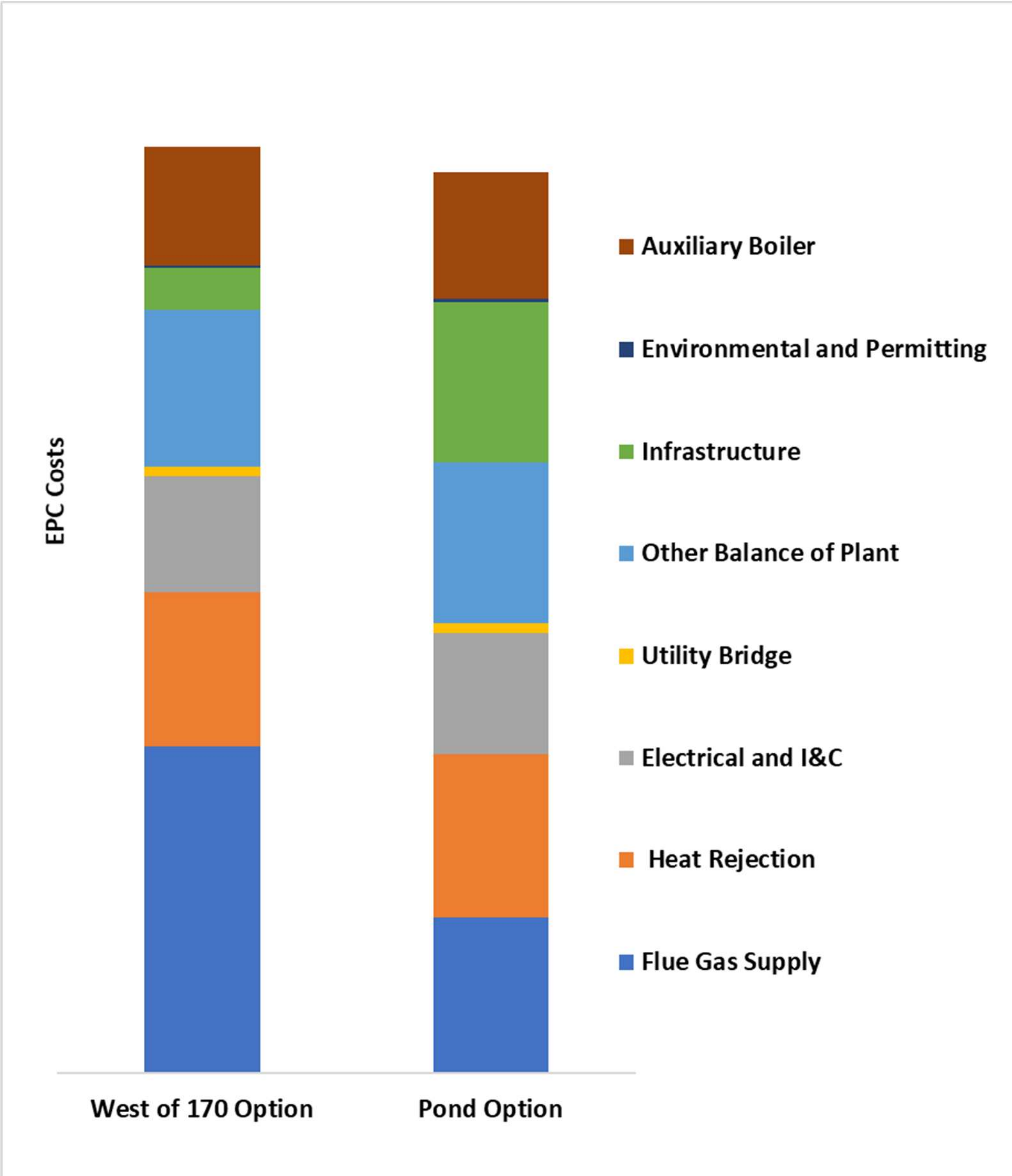


FIGURE 11.1 BOP SYSTEMS CAPITAL COST BREAKDOWN BY SCOPE

11.1.3 Construction Capital Cost

The total construction capital costs of the CO_2 capture plant and BOP systems for the west of 170 and pond options are shown in Figure 11.1. These numbers are presented in 2021 dollars (no escalation), and do not include contingency, escalation, interest, or owner costs.

TABLE 11.1 TOTAL CAPITAL COST ESTIMATE

Item	West of 170 Option	Pond Option
Construction Capital Cost	$ 639.2M	$ 643.3M

11.2 Operating Costs

An estimate of the expected cost to operate the CO_2 capture plant and BOP systems was prepared as part of this study. Four separate cases were considered, and operating costs (in 2021 dollars) were categorized as either fixed or variable costs (See Table 11.2) and are described in more detail below.

TABLE 11.2 PROJECTED OPERATING COSTS

Item	Design Case		Operating Case	
	West of 170	Pond Option	West of 170	Pond Option
Fixed Operating Costs	$9.69M	$9.69M	$9.59M	$9.59M
Variable Operating Costs	$26.80M	$26.60M	$24.85M	$24.65M
Annual Operating Costs	**$36.49M**	**$36.28M**	**$34.44M**	**$34.24M**

11.2.1 Fixed Operating Costs

Fixed operating costs cover items associated with the plant which generally do not vary with the amount of flue gas treated or the amount of CO_2 captured. Fixed costs include permanent plant staffing costs, property taxes and insurance, and operational and planned maintenance costs including annual maintenance outages. Natural gas transmission costs were treated as fixed costs, based on the assumption that the plant would contract for firm gas transmission delivery service to a level where interruptible transmission capacity would rarely be utilized. The contribution of each of the fixed cost components to the total for the west of 170 option are summarized in Figure 11.2.

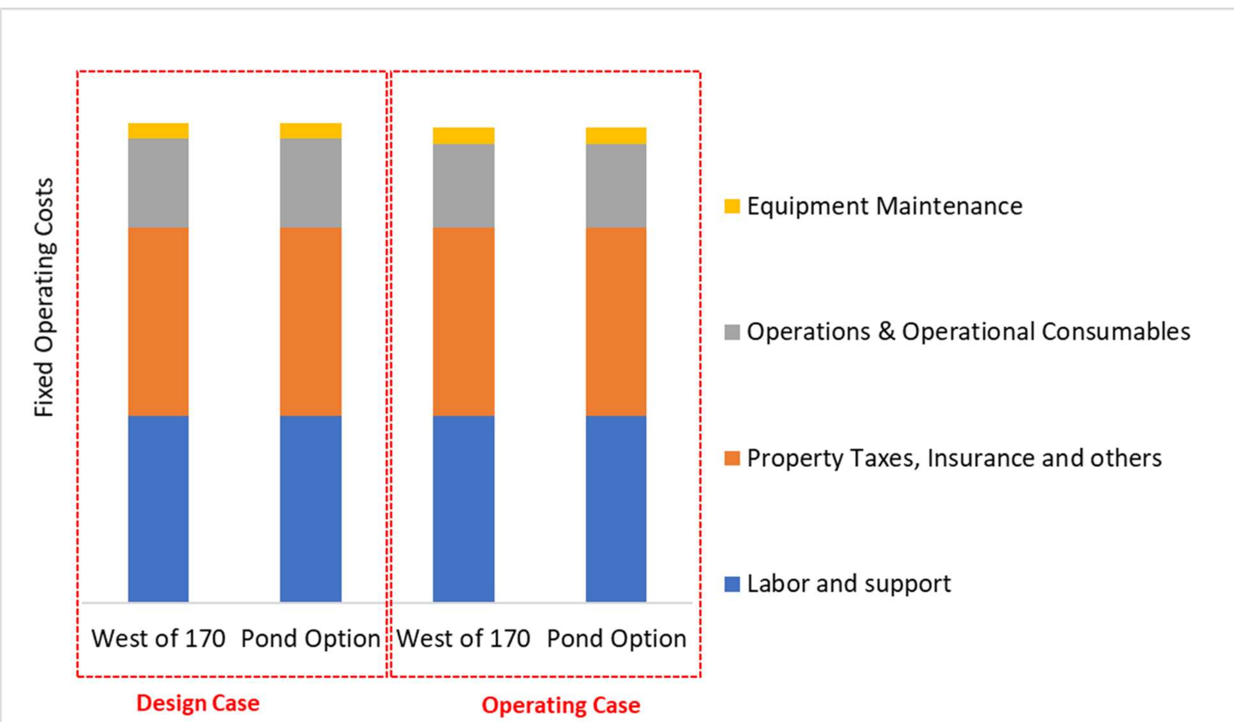


FIGURE 11.2 SUMMARY OF FIXED OPERATING COSTS

11.2.2 Variable Operating Costs

Costs categorized as variable are those that are directly affected, although not necessarily proportional to, the amount of flue gas treated or the amount of CO_2 captured. About 70% of the variable operating costs are energy costs associated with natural gas consumption in the auxiliary boiler and electrical power consumption for the CO_2 capture plant and BOP systems.

The cost of power was based on predicted energy consumption and 15-minute peak demand and the unit rates applied to these parameters. The electrical energy consumption and the electrical power demand were estimated for the CO_2 capture plant and the BOP systems for each month of a typical year. The monthly breakdown was required in order to simulate the effects of ambient temperature on power requirements for the heat rejection system (lower power requirements in cold temperature conditions and higher in hot).

Natural gas costs were developed in a similar manner to electricity. Natural gas consumption, mostly in the auxiliary boiler, and to a small degree for building heat, was estimated based on the number of hours of operation in each month. The variable operating costs for the four cases analyzed are summarized in Figure 11.3.

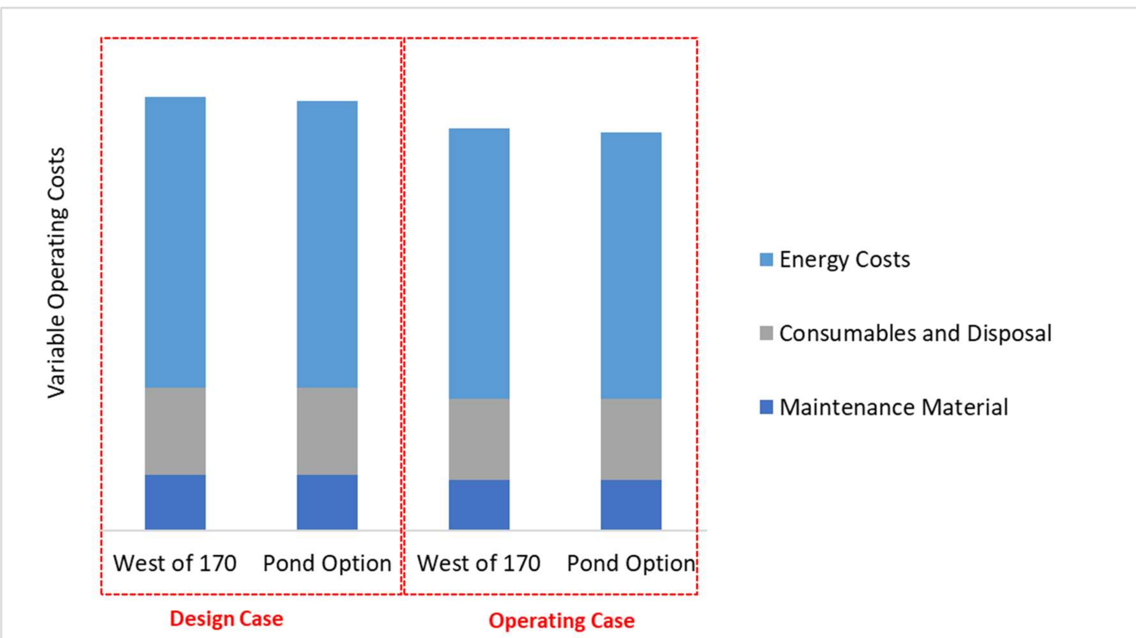


FIGURE 11.3 SUMMARY OF VARIABLE OPERATING COSTS

Chapter 12 Project Outcomes

12.1 Environmental and Greenhouse Gas Benefits

The objective of this project was to study the addition of a CO_2 capture plant that will remove 95% of the CO_2 emissions from the flue gas from the existing kiln, as well as the new auxiliary boiler installed to support the energy requirements of the capture process. The pretreatment required to enable CO_2 capture also reduces other emissions which will be further described in the following sections.

12.1.1 CO_2 Emission Reductions

The annual CO_2 emissions of the Lehigh Edmonton Cement Plant varies with the clinker production rate, market demand, and the type of fuel being consumed. For the purpose of this study, the CO_2 capture plant was sized to capture up to 780,000 tonnes per year of CO_2 based on the use of natural gas as the fuel source.

12.1.2 Other Emission Reductions

The CO_2 capture process requires pre-treatment of the flue gas to minimize degradation of the amine solvent, and ensure reliable and efficient operation of the capture system. This pre-treatment process has the side benefit of substantially reducing the atmospheric emissions of several contaminants. Table 12.1 illustrates the current emissions in the kiln flue gas and the expected emissions after the implementation of carbon capture.

Table 12.1 Kiln Flue Gas Emissions for the Design Case Before and After Carbon Capture

	Unit	Design Kiln Flue Gas Emissions Before Carbon Capture	Flue Gas Emissions After Carbon Capture
SO_X	ppm	6.29	<1
NO_X	g/s	111	113[1]
Condensable Particulate Matter (CPM)	mg/Nm^3 dry	215.6	<1
Filterable Particulate Matter (FPM)	mg/Nm^3 dry	6.4	<1

Note[1] Additional 2 g/s NO_X produced by the auxiliary boiler

The overall result has been to largely eliminate emissions of SO_X and particulate while creating minor levels of additional emissions in the form of NO_X. Dispersion modelling indicated that the NOx contribution to ambient emissions levels associated with this project will be less than 54% of AAAQO.

12.2 Design Constraints and Optimizations

12.2.1 Location

The Lehigh Edmonton Cement Plant site is a constrained brownfield site located within a major urban center. This location poses a number of risks, from increased capital cost due to the limited area available for the CO_2 capture plant, public perception issues related to the new equipment, and potential impacts to cement plant operations during construction and future operation. After the initial desktop siting study, two locations were studied in more detail: 1) the east end of the existing water pond, named the pond option, and 2) 1 km west of the existing cement facilities, named the west of 170 option.

There were capital and operating cost differences between these two options. The west of 170 option required a long flue gas duct, which added capital cost, and a larger booster fan which increased power consumption. These significant cost increases were offset by improvements in construction efficiency allowed by additional available space. The pond option required the creation of a second pond west of 170 resulting in significant challenges to maintain functionality of the pond systems during the transition to, and construction of, the CO_2 capture plant. The construction plan for the pond option required a sequence of coffer dams which added to the cost and complexity of the pond option. As outlined in Chapter 11, the difference in capital cost between these two options is negligible given the accuracy of the Class 4 cost estimate.

12.2.2 Waste Heat Recovery

The CO_2 capture process has significant thermal energy requirements and waste heat recovery was investigated as a potential source for this energy. The two sources of waste heat considered were the kiln flue gas conditioning tower and the hot air coming from the clinker cooler. While these two locations could provide low emission heat and reduce the fuel requirements, the capital and maintenance costs for waste heat recovery were significant. Waste heat recovery was only able to supply about 15% of the steam required by the CO_2 compressor steam turbine and the reboiler used for solvent regeneration. The annual natural gas savings with waste heat recovery would be $1.67M. The installed cost of the two WHR units was estimated at $69.2M. Therefore, installation of the WHR units is not economically feasible.

12.2.3 Steam Driven CO_2 Compressor

The CO_2 compressor is a large consumer of energy, and a steam turbine driven compressor was identified as an attractive option for this project. The advantage of the steam turbine is that it can utilize the steam generated by the auxiliary boiler before it is used for solvent regeneration. The steam must be at higher pressure and temperature for the steam turbine, but the additional energy can be obtained with an effective efficiency of 83%. This efficiency is much higher than a typical thermal power plant (~40-45%) that would provide electricity to the Alberta Electric System Operator. The additional CO_2 generated from the incremental steam generation will also be captured in this application.

The cost of electricity relative to the base case is significantly reduced when a steam driven compressor is used as shown in Table 12.2.

TABLE 12.2 TOTAL ENERGY COST COMPARISON OF ELECTRICAL AND STEAM DRIVEN COMPRESSOR

Item	Electrical Driven Compressor	Steam Driven Compressor
Natural gas cost	Base	118%
Power cost	Base	50%
Total cost of natural gas and power	**Base**	**68%**

A comparison of CO_2 emissions intensity per tonne of clinker produced with the addition of carbon capture is shown in Figure 12.1. With the integration of carbon capture, direct CO_2 emissions are reduced to 43 and 45 kgCO_2/ tonne clinker for the electric and steam driven compressor options respectively. The indirect CO_2 emissions are increased with the addition of the CO_2 capture plant. These emissions cannot be controlled by Lehigh but are minimized with the selection of a steam driven compressor.

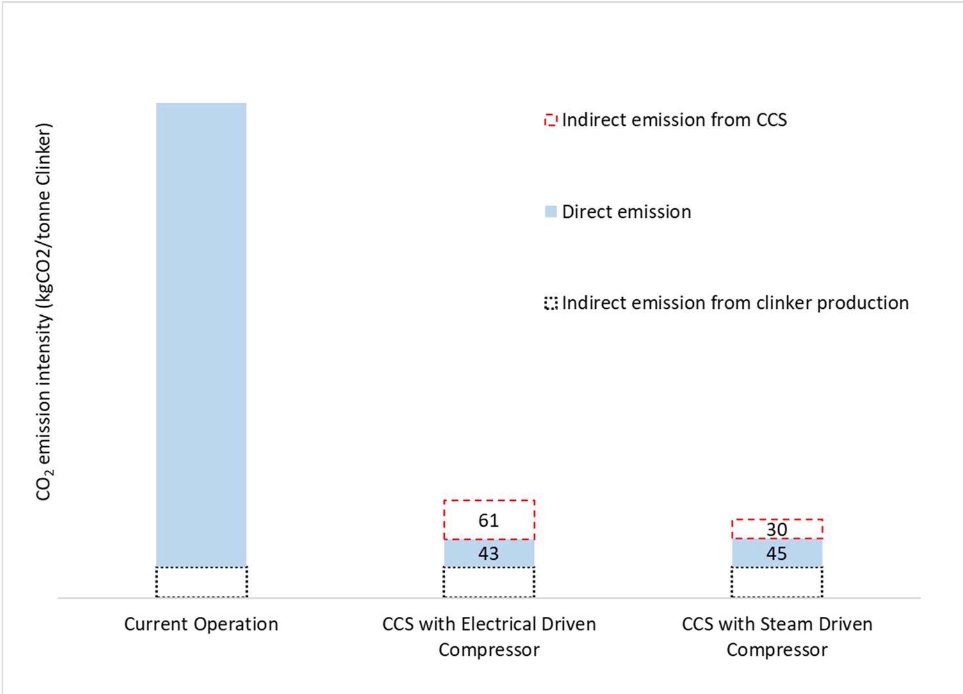


FIGURE 12.1 CO_2 EMISSION INTENSITY PER TONNE OF CLINKER

In addition to the natural gas and power costs described above, there are two additional factors related to the selection of a steam driven compressor; the capture plant size and the electrical infrastructure requirements.

12.2.3.1 CO_2 Capture Plant Size

The electrical driven compressor option utilizes a smaller auxiliary boiler resulting in less CO_2 produced for the CO_2 capture plant. As a result, the BOP and capture systems would be approximately 3-5% smaller for the electrically driven compressor case

12.2.3.2 Electrical infrastructure

The size of the electric compressor drive motor would have required that the 138 KV electrical supply doubles in size. This increased load would require the addition of two 138 kV / 13.8 kV transformers and switchgear to the current substation to create an adequate 13.8 kV bus. The higher load would also increase the cost of the included source substation modifications and the new transmission line. These additional costs for the substation and infrastructure were estimated to be about $700,000.

12.2.4 Carbon Capture Technology

12.2.4.1 High CO_2 Capture Rate

The conventional post combustion amine-based CO_2 capture processes utilized at the BD3 CCS Facility and Petra Nova, are both designed to capture CO_2 at a capture rate of 90%. The desired capture rate was discussed early in the project and a design capture rate of 95% was selected, as recent study work by the Knowledge Centre for the Shand CCS Feasibility Study has shown that 95% capture is possible, with a minimal impact to the cost of CO_2 capture. The analysis completed for this study led the capture technology vendor, MHI, to confirm that a 95% CO_2 capture rate is suitable for this project. The capture rate for the plant should be reexamined in a FEED study to ensure that the optimal plant size is selected to balance capital costs, operating costs and annual CO_2 captured.

12.2.4.2 Flue Gas Pretreatment

Operating experience from the amine-based CO_2 capture at the BD3 CCS Facility has shown that impurities in the flue gas can result in unplanned emissions and costly degradation of the amine solvent. These risks can be mitigated by including appropriate flue gas pre-treatment.

The cement kiln flue gas may have a high concentration of particulates including CPM and FPM. These particulates can contribute to amine emissions as they act as nuclei for the formation of amine droplets. CPM and FPM can be reduced by the flue gas quencher, however the remaining particulates may still lead to amine emission. The design includes the addition of a WESP to remove CPM and FPM and mitigate the risk of amine degradation. At the time of this study, the results from a detailed stack test were not available. The requirement for this pre treatment equipment should be verified as part of a FEED study that examines the results of the stack test.

12.2.4.3 Steady State-Kiln Operation vs. Variable Load with Power Generation

The interruptible, but steady-state operation of the kiln presents different operating conditions to the CO_2 capture plant compared to experience at electrical generating plants.

The steady-state operation associated with a cement plant is more energy-efficient during operation when compared to existing installations on electrical generating units that operate in a variable output mode fluctuating between 70% and 100% of maximum output. Operating in a variable output manner presents a fluctuating amount of flue gas to the CO_2 capture plant, as well as varying steam supply temperatures and pressures to the reboilers due to heat recovery and steam cycle integration. These varying conditions require a more complex control system and increase the energy requirements per unit of CO_2 for capture and compression. At lower flue gas flow rates, solvent recirculation rates do not reduce proportionately so pumping energy requirements per unit of CO_2 captured increase. In addition, the CO_2 compressors do not have a very wide turn down before recirculation of CO_2 must be undertaken to maintain stable compressor operation. During recirculation, the compressor drive power requirements remain high, increasing the per unit energy requirement for compression. In contrast, the input flue gas flow rate at a cement plant is more constant. Control systems are simplified and per unit energy consumption is minimized because the system operates near optimized design conditions.

However, while cement production is more constant in terms of output, kiln clinker production is interrupted more frequently due to changes in supply requirements when compared to electrical generating plants that strive for availability of greater than 90%. This results in less CO_2 captured in a year simply due to lower availability of the flue gas supply, driving up the overall cost of capture on a per tonne basis for a cement plant compared to electrical generating plants.

12.2.5 Lessons Applied

Several lessons learned from the design and operation of other projects such as the BD3 CCS Facility, Petra Nova, and the Shand CCS feasibility study, were applied to this study. These design considerations included proper flue gas pre-treatment, water and waste management, sufficient redundancy, optimized sizing of equipment, and material selection to optimize cost and durability.

Proper flue gas pre-treatment is required to minimize solvent degradation and losses. A wet electrostatic precipitator (WESP) was included in the process design, for example, which is a technology that was not included in previous projects, but could have helped projects such as BD3. Experiences from the BD3 also illustrate the need for longer-term piloting to validate process decisions. Evaluating the results of the completed stack test in the next phase of this project would confirm if the WESP is required, or if other, less capital-intensive pre-treatment strategies will be suitable for the Lehigh project.

Water and waste-water management is a challenge for any CCS project and in the case of the Lehigh study, learnings from the Shand CCS Feasibility study were applied. This included a hybrid wet/dry cooling system that could be used to consume water condensed from the flue gases, reducing the quantity of water to a manageable amount that could be consumed in the cement making process, avoiding the need to store or dispose of waste water.

The heat rejection system was optimized for an 85th percentile ambient temperature, rather than the maximum expected ambient temperature. This came from the Shand CCS feasibility study which had shown that a reduced size of heat rejection system would result in considerable savings in capital and operating costs for the heat rejection equipment, while the incremental CO_2 emissions at higher ambient temperature would be insignificant.

Additional redundancy was added for the Lehigh project based on the experiences from the BD3 project, including heat exchangers and pumps and the isolations necessary to allow for online service. This redundancy was ultimately applied to the BD3 project to minimize the capture plant outages, but the cost for these upgrades after the initial construction was many times higher than it would have been had it been included in the initial design.

Material selections considered the experiences from previous projects such as Petra Nova and BD3 as well as the cement plant. Material selection for the flue gas duct is one example and materials for valves to maximize durability would be another.

Heat integration was an important aspect of previous projects. While waste heat recovery was found to not be economic for this project, the selection of a steam driven compressor did provide significant benefits in operating costs and indirect CO_2 emissions.

12.3 Capital Cost Factors

12.3.1 Available Space and Relocation of Pond Infrastructure

The limited space available at the site cannot be ignored as a cost factor. Capital costs would be reduced for locations or facilities that have more available space for the required capture equipment.

12.3.2 New Infrastructure Not Typical of Cement Plant

The Lehigh Edmonton Cement Plant site, and most cement plants, handle mainly dry materials and have limited cooling and water treatment systems, and typically no steam production. The new auxiliary boiler, heat rejection and related water treatment systems, all atypical of a cement plant, made up almost half of the BOP additions. These new systems will require additional operational knowledge for the facility.

12.3.3 Fouling Risk Mitigation

The capture and compression systems included several additions to mitigate risk. Based on the experiences at the BD3 CCS Facility, a redundant wash water cooler, and a lean amine cooler were added. In addition, multiple lean rich heat exchangers and lean and rich amine pumps were added to allow on-line cleaning. These additions are included as they can be completed as part of the initial construction at a fraction of what it would cost to add after project commissioning.

12.3.4 Emission Risk Mitigation

The capture plant design included a WESP and additional absorber wash sections to mitigate particulates and aerosols pending additional stack and pilot testing. The additional testing may show that more cost-effective flue gas pretreatment steps such as dry sorbent injection would be sufficient and would substantially reduce the capital cost of this project. As mentioned previously, the flue gas treatment requirements should be reviewed as part of a FEED study after the recommended stack testing is complete.

12.4 Operating Costs

Fixed and variable operating costs are substantial at $36 million per year. The distribution of operating costs across energy, fixed, consumables and disposal, and maintenance costs is illustrated in Figure 12.2.

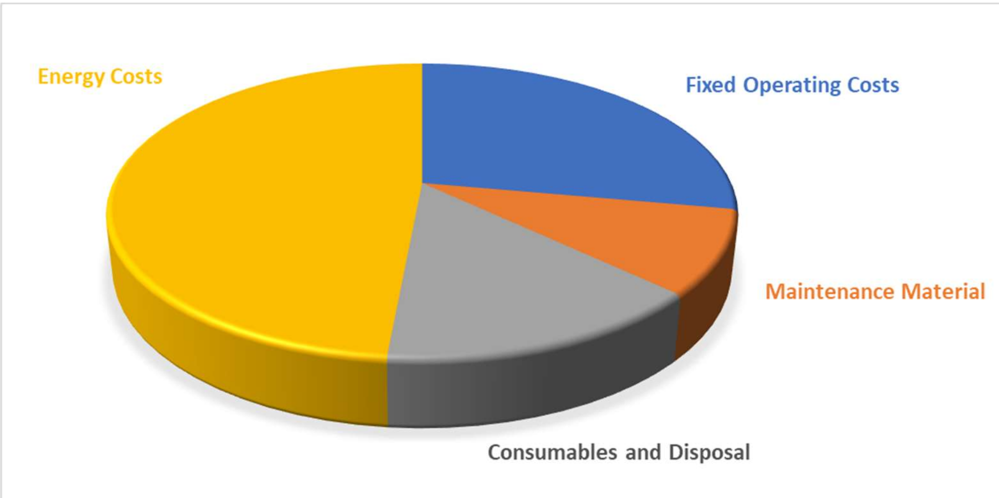


FIGURE 12.2 THE OPERATING COSTS FOR THE CO_2 CAPTURE PLANT PER TONNE CO_2

12.4.1 Opportunities to Reduce Electricity and Natural Gas Cost

Together, electrical and natural gas represent almost half of the annual operating cost. The costs of these commodities have historically been quite volatile, and this volatility is an issue that needs to be addressed. Other projects such as the BD3 CCS Facility and the Petra Nova CCS project have utilized electricity generated at the site and lower grade heat that is available from the power generation process. In the case of the BD3 CCS Facility, the CO_2 capture plant and existing power plant were fully integrated, while a new gas turbine and heat recovery steam generator were installed for the Petra Nova CCS project, to supply both the power and heat for the capture project.

The addition of a combined heat and power plant could eliminate the cost of purchased electricity and make better use of the energy in the natural gas consumed at the site. The CO_2 from the power plant would be captured, resulting in near zero emissions electricity and reduced scope 2 emissions for the overall plant. The addition of a combined heat and power facility should be examined as part of the FEED study.

12.4.2 Labour Costs

The third largest operating cost for the project is the labour. Opportunities to reduce these costs may be limited but such opportunities should be investigated during the FEED study.

12.5 Economic Benefit to Alberta

12.5.1 Economic Benefit from Construction and Operations

If the project proceeds to construction, it will include significant industrial construction work, both on-site as well as utilizing vessel and module fabrication yards that have traditionally serviced the construction needs for oil sands expansion. The BD3 CCS Facility in Estevan, Saskatchewan saw nearly five-million-person hours of work on-site during construction. For the Lehigh Edmonton CCS project, the preliminary construction schedule (Level 1 schedule) shows the requirement of 36 to 40 months of on-site construction. The direct employment is expected to exceed two-million-person hours during the construction phase

The estimated operating costs for the carbon capture and compression systems, up to and including delivering super-critical compressed CO_2 to the property line of the plant, are estimated to be $34.5-$36.5M per year. The operation of the plant would create in the range of 25 new permanent full-time jobs, while annual maintenance and turnaround activities will create further employment on an annual basis.

12.5.2 Revenue

The project is considering various avenues to help offset some of the investment costs, including:

Permanent Sequestration Utilizing Enhanced Oil Recovery (EOR)

The Lehigh Edmonton CCS project will produce compressed CO_2 of suitable purity for permanent sequestration utilizing EOR which could offer a return for the project. To date, the production of CO_2 for beneficial re-use has been a highly effective driver for CCS projects, especially in North America. Of note, it is well known that the oil field's potential use of CO_2 in the region is abundant and the additional, low-emitting recovery of oil using EOR is proven. Additionally, the Alberta EOR royalty/tax regime provides an additional incentive.

When considering CO_2 for EOR, a significant investment in pipeline infrastructure and drilling work, as well as upgrades to oil batteries and other surface facilities is necessary. While this work is outside the scope of the study, it could have a direct result in the investment decisions for the facility.

Emissions Reduction Credits and Offsets

When a capture facility is attached to the cement plant, the emissions increase because there is more energy required to capture the CO_2. Under Alberta's Technology Innovation and Emissions Reduction (TIER) program, various emission performance and/or offset credits can be used to satisfy compliance. Under the current TIER system, such credits for the sequestered CO_2 that has been captured will default to the sequesterer so any credit allocation will need to be negotiated with the CO_2 off takers.

Grants, Incentives and Financing

In Budget 2021, the Canadian government proposed the introduction of an investment tax credit (ITC) for capital invested in carbon capture, utilization and storage (CCUS) projects, and $319M over seven years through an Energy Innovation Program (EIP), with the goal of reducing emissions by at least 15Mt of CO_2

annually.[5] Other Canadian programs such as the Strategic Innovation Fund (SIF) and the Net Zero Accelerator initiative are tailored to support business development projects that promote decarbonization of large emitters.[6] The ability to leverage and stack both federal and provincial programs may help to enable the Lehigh project.

Premium Grade Cement

Once the project is operational, the cement produced by the Lehigh Edmonton plant is expected to be both in high demand and sell at a premium due to its verifiable low carbon footprint, resulting in additional value coming into the province.

12.5.3 Knowledge Transfer

The lessons learned and commercial innovations developed to adapt CO_2 capture to the unique challenges of a cement facility will be invaluable to advancing the global understanding of and business case for the application of CO_2 capture technology. Successful completion of a commercial-scale CO_2 capture plant at the Lehigh Edmonton plant can help accelerate the technological and economic case for applying CCUS across countless other hard-to-abate sectors in Alberta and around the world, significantly multiplying the economic and environmental benefits of the project.

[5]https://www.canada.ca/en/department-finance/programs/consultations/2021/investment-tax-credit-carbon-capture-utilization-storage.html

[6] http://www.ic.gc.ca/eic/site/icgc.nsf/eng/home

Chapter 13 Conclusions

The Lehigh Edmonton CCS Feasibility study was completed for Lehigh by the Knowledge Centre with funding support from Emissions Reduction Alberta. The main conclusions of the feasibility study are:

- AACE Class 4 capital and operating cost estimates for the addition of a carbon capture and compression plant at the Edmonton Cement Plant were developed. The construction capital cost estimate for the recommended location was $639 million not including escalation, contingency, interest, and owner costs. The annual operating cost was $36.5 million.
- The carbon capture process as designed during the feasibility study can capture 95% of the CO_2 from the existing kiln, as well as from a new auxiliary boiler that required to support the capture and compression process. The CO_2 capture plant will capture 780,000 tonnes of CO_2 per year.
- The process design for the capture process included predictions of the CO_2 product composition and impurities, and the composition is within accepted ranges for permanent sequestration or for EOR.
- The use of waste heat in the existing cement plant to generate steam for the CO_2 capture plant was investigated. Although the technology is mature and practical, there is insufficient heat energy available, and the capital and operating costs are too high for it to be economically feasible for this project.
- A hybrid heat rejection system was developed that would use a combination of dry cooling with air-cooled heat exchangers and wet cooling with wet surface air coolers. The wet cooling would use water recovered from the flue gas thus avoiding the need for disposal. Wet cooling does allow a lower cooling water temperature to be achieved, improving the performance of the CO_2 capture plant.
- Available space at a potential site is a significant factor when evaluating the feasibility of adding carbon capture to an existing industrial facility. The Lehigh Cement Plant has limited space available, and several sites were investigated for the CO_2 capture plant and the BOP systems. A suitable location was identified, however it is not near the emission source within the cement plant and the additional infrastructure required increased the CAPEX relative to a facility that could accommodate the new equipment nearby.
- Significant cost savings can be realized for this application by using a steam-driven CO_2 compressor rather than using an electric motor drive. The analysis resulted in significant annual OPEX savings.
- The addition of a standalone steam generator to support the CO_2 capture plant increases the overall cost of this project. **There is an opportunity to significantly impact the overall cost of capture by examining the addition of a combined heat and power facility.**

Table 13.1 summarizes the success metrics that formed the basis for the study and the outcomes.

TABLE 13.1 SUCCESS METRICS

Success Metric	Target	Outcomes
Capture efficiency	Plant designed to capture 95% of CO_2 in exhaust gas.	Achieved
CO_2 capture plant capacity	Plant designed to handle peak CO_2 production associated with the Edmonton facility.	Achieved
Waste Heat Recovery-cost	Cost to build and operate waste heat recovery system is less than or equal to cost to build and operate gas fired boiler.	Design and costs estimates were completed but waste heat recovery is not economic
BOP sysems – layout	Capture plant will fit in available footprint.	Achieved
BOP systems – heat rejection	Sufficient resources available to reject heat from regeneration process.	Achieved
CO_2 product quality	CO_2 quality acceptable for beneficial reuse such as EOR.	Achieved
Feasibility study – capital and operational cost estimate	Project costs identified to class 4.	Achieved

Chapter 14 Risks and Opportunity

The feasibility study into the applicability of carbon capture technology at the Lehigh Edmonton facility has been completed. The following risks to project execution have been identified:

14.1 Project Risks

Table 14.1 Project Risks and Mitigation

Risk	Mitigation
Approvals from the City of Edmonton for 170 St. crossing may delay or rule out this option	Engage early with City of Edmonton Further examine the bridge and underground options for discussions with the city
Pond construction may put plant cooling water supply at risk	Stage the pond construction to eliminate this risk
Availability of trades could have cost and schedule impact	There is a large labour pool in the Edmonton area, engage with labour organizations prior to FID
Congested work area could lead to cost and schedule impacts	Plan staged construction to minimize this risk, transfer this risk by using an EPC execution strategy, the west of 170 location reduces this risk
Congested work area could lead to plant operation impacts	Include penalty in EPC contract for operations impact, the west of 170 location reduces this risk
Weather risk	Plan schedule for summer construction
High voltage Power and Natural Gas supply require long lead times for interconnection	Engage with utility providers early in the FEED study and get into the interconnection queues
The CO_2 capture plant design capacity is higher than the historical average production rate	Review the design capacity of the CO_2 capture plant and the planned production rate to ensure that the plant size is optimized while ensuring reliable operation

14.2 Next Steps

The recommended next steps are listed below.

14.2.1 Front End Engineering Design Study

Following the completion of this feasibility study and approval from Lehigh's management team, the next step to move forward with the Edmonton CCS Project is to undertake a Front End Engineering Design (FEED) Study. The output of the FEED study will be a more defined cost estimate (AACE Class 3) that is suitable for a final investment decision. The FEED study should include a pilot-scale test to validate amine degradation with the specific flue gas from this facility.

14.2.2 Combined Heat and Power Opportunity

There are a number of design details that can be optimized through a FEED study. However, the larger opportunity to optimize this project is to incorporate combined heat and power (CHP) technology. A combustion turbine, combined with a heat recovery steam generator sized to match process and compression steam demands, exhausting flue gas into the CO_2 capture plant could yield several benefits to the project:

1) The overall efficiency of natural gas utilization remains high at approximately 85%
2) The electrical energy costs for the carbon capture process are substantial, and self-generation of electricity would reduce this cost to Lehigh
3) There may be surplus electrical energy available for sale to the system operator providing an additional revenue stream improving project economics
4) If care is taken to ensure the plant qualifies as a CHP, the carbon credits (difference between allowable untaxed emission intensities as a CHP and actual emissions after carbon capture) would be marketable and a potential revenue stream
5) Almost eliminates the indirect CO_2 emissions of the electrical energy component of carbon capture based on current Alberta grid emission intensity

Chapter 15 Communications Plan

15.1 Communication Activities during the Feasibility Study

A number of communications and key knowledge-sharing activities were undertaken during the study:

Onsite Tri-Partner Media Announcement Event

- The event included presentations and bannered photo opportunities with Lehigh, ERA, and the International CCS Knowledge Centre.
- The announcement was supported by a news release*, Lehigh Cement and the International CCS Knowledge Centre Pioneering a Feasibility Study of Full-Scale Carbon Capture Storage (CCS) on Cement* (NOV 28, 2019). Members of the media were provided with interviews, background information, and follow-up opportunities.
- This news release was distributed across international wires and translated into six languages.
- This announcement was supported with social-media campaign and newsletter distribution.

Web Page to Initiative

- A dedicated web page was created for the Feasibility Study; CCS on Cement – Lehigh CCS Feasibility Study
- This landing page is redistributed via social media campaigns and used as home for additional posting to website for related initiatives, such as the call for expression of interest

News Release

- *Low Carbon on Cement Possible with CCS* (JAN 21, 2021) with Lehigh & MHI
- This news release was distributed across international wires and translated in six languages.
- This announcement was supported with social-media campaign and newsletter distribution.

Carbon Capture on Cement Specific Articles

- Article written for and published in International Cement Review, *Large-Scale CCS for Lehigh* (FEB, 2021)
- Article on *Powering Amine Regeneration with Waste Heat Energy for CCS on Cement* (APR, 2021)
- These articles were supported with social-media campaigns and newsletter distribution.

Submissions of Abstracts/Papers to IEAGHG Technical Conference and Forum

The Greenhouse Gas Control Technologies 15 (GHGT-15) conference

- A Feasibility Study of Full Scale, Post Combustion, Amine Based, CO_2 Capture Retrofit Application in the Cement Manufacturing Sector at the Lehigh Hanson Materials Limited Facility

The IEAGHG Post Combustion Capture Conference 6 (PCCC6)

- Waste Heat Utilization for the Energy Requirements of a Post Combustion CO_2 Capture Retrofit Study at the Lehigh Hanson Cement Manufacturing Facility in Edmonton, Canada
- Srisang, W., Giannaris, S., Feng, Y., Janowczyk, D., Bruce, C., & Jacobs, B. (2021). A Feasibility Study of Full Scale, Post Combustion, Amine Based, CO_2 Capture Retrofit Application in the Cement Manufacturing Sector at the Lehigh Hanson Materials Limited Facility. Post Combustion, Amine Based, CO_2.

https://ccsknowledge.com/resources

Mentions in Numerous Communication Activities
These inclue but are not limited to: media interviews, articles, blogs, and Knowledge Centre publications, (such as: Incentivizing CCS in Canada) since the announcement in 2019.

Additionally, the project has been a keen topic of interest in a multitude of presentations, webinars, international conferences, as well as through direct engagement with industry, government, and various associations.

15.2 Plans for Communicating

As forerunners in the application of large-scale CCS on a cement plant, this joint initiative toward advancing the Edmonton CCS Project (by Lehigh, ERA, and the Knowledge Centre) provides an opportunity to showcase individual and collective leadership of these organizations in climate action, carbon capture technology and knowledge for its adaptation to other industrial processes.

The communications objectives for the Lehigh CCS Feasibility Study include:

- To garner interest and acclaim from the top results of the Lehigh CCS Feasibility Study as critical/turning point learnings to actively launch the Edmonton CCS Project toward and into the FEED phase.
- To promote the value of know-how gained through the understanding for each of the identified outcomes of the feasibility study and demonstrate Lehigh's, ERA's, and the Knowledge Centre's commitment to climate change action.
- To inform the public, business communities, and governments about the importance of investment in large-scale CCS applied to industrial sources as a go-to-technology and climate change mitigation tool.
- To showcase the proposed carbon capture facility at Lehigh as a forerunner in carbon capture on cement in the world and the first in North America as tied to climate change mitigation, corporate responsibility, and environmental sustainability.

The communications approach for the Lehigh CCS Feasibility Study encompasses campaigns, (activities, products, and strategy) chosen depending on the needs required to deliver on each of the communication objectives. Some of the key elements include a media release acknowledging the publication of the study and contributions by partners, online and social media campaigns, presentations through webinars and conferences, notably at the IEAGHG's Post Combustion Capture Conference in October 2021, as well as at the Conference of the Parties (COP 26) to the United Nations Framework Convention on Climate Change in November 2021.