November 2021

SUMMARY FOR DECISION MAKERS ON LARGE-SCALE CCS ON CEMENT

Based on Lehigh Edmonton CCS Feasibility Study

INTERNATIONAL CCS KNOWLEDGE CENTRE

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ACKNOWLEDGEMENTS

The International CCS Knowledge Centre (the Knowledge Centre) acknowledges that the content for this short report is a high-level summary of the expansive and detailed Lehigh Edmonton CCS Feasibility Study. That study examines the feasibility of adding a full-scale carbon capture plant at Lehigh's Edmonton Cement Facility and was a joint initiative of the Knowledge Centre and Lehigh Hanson Materials Limited (Lehigh), with funding support from Emissions Reduction Alberta (ERA).

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INTRODUCTION

As the world turns to collective and rapid action to make meaningful reductions in anthropogenic greenhouse gas emissions (GHGs), large-scale carbon capture, utilization, and storage (CCS/CCUS) is proving its role in substantial emission reductions in the energy and emerging industrial sectors. The cement industry is taking notice and formulating a pathway for CCS as an active contributor to goals for carbon neutral cement.

This document is a summary for decision makers based on the Lehigh Edmonton CCS Feasibility Study.

The Lehigh Edmonton CCS Feasibility Study, jointly conducted by Lehigh Hanson Materials Limited (Lehigh) and the International CCS Knowledge Centre (the Knowledge Centre), is aimed at 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 project is an important breakthrough for large-scale CCS and represents a first in North America for CCS application in the cement industry.

The main deliverable of the feasibility study was 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 capturing up to 780,000 tonnes/year CO_2. The feasibility study concluded that amine post-combustion capture technology can capture up to 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 study resulted in an estimated construction cost of ~**CDN**$640M not including owner's costs (e.g. engineering, project management), escalation (i.e. inflation), contingency, insurance, or the interest during construction (IDC). The preliminary capture plant design concluded that the captured CO_2 quality would be compatible with safe and permanent storage in a deep geological saline aquifer. Additionally, the selected location proposed for the capture plant would require minimal disruptions to operations during construction and the necessary tie-ins could be completed during routine planned downtime.

With a budget of **CDN**$3.0M, funding for the feasibility study was received via an investment of **CDN**$1.4M from Emissions Reductions Alberta (ERA), as well as funding from Lehigh.[1]

The Knowledge Centre, a globally recognized leader in post-combustion CCS development, provided project management and advisory services for this study. The Knowledge Centre engaged an experienced CO_2 capture technology vendor, Mitsubishi Heavy Industries (MHI) Group, for the design of the CO_2 capture system. MHI was responsible for the CO_2 capture plant scope of work that included the flue gas pre-treatment system, the CO_2 capture and compression process. The Knowledge Centre also worked with Kiewit Corporation, one of North America's largest and most respected engineering and construction companies, to complete the balance of plant (BOP) portion of the study, and with Sinoma Heat Energy Conservation Ltd. to examine the potential to utilize waste heat.

The Knowledge Centre utilized its experience from both the fully integrated SaskPower Boundary Dam 3 (BD3) CCS Facility and the second-generation CCS feasibility study at the SaskPower Shand Power Station (Shand Study) to provide direction and guidance towards this project. Both the BD3 CCS Facility and the Shand Study are frequently cited throughout this document. The BD3 CCS Facility is the world's first utility-scale, fully integrated post-combustion carbon capture facility on a coal-fired power plant. The CCS story at the BD3 CCS Facility is one of an evolution towards improvement, both in construction and operation. The addition of carbon capture transformed Unit 3 at Boundary Dam Power Station into a long-term producer of more than 110 megawatts (MW) of low emissions base-load electricity. The Shand Study examined the feasibility of retrofitting the Shand Power Station, a 300 MW, single unit, coal-fired power plant that has double the capacity of the BD3 CCS Facility. In comparison, a future CCS system install at Shand could see life cycle capture cost reductions of greater than 50% per tonne of CO_2 captured.

Intended Outcome

To advance to a front-end engineering and design study (FEED) stage to support the design to build a world leading, cost effective integrated carbon capture facility on a cement plant to significantly reduce CO_2 emissions at location and to share and export the gained knowledge to see exponential emission reductions in the industrial sector world-wide.

ABOUT LEHIGH CEMENT & LEHIGH HANSON

Lehigh Cement, which is part of Lehigh Hanson Inc., hosted 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 Hanson represents the North American operations of HeidelbergCement AG, which is one of the world's largest building materials companies. At the heart of its core environmental policies is climate change protection and the progress towards carbon neutral cement. The company is committed to fulfilling its share of global responsibility to keep temperature rise below 1.5ºC with a commitment to a 30% reduction in its CO_2 emissions by 2025, compared to 1990 levels and carbon neutral concrete by 2050. Current conventional methods to reduce Lehigh's GHG emissions are not nearly enough to reach carbon neutrality. For this reason, the deployment of CCS is required to ultimately reduce hard-to-abate emissions in order to produce carbon neutral cement.

Lehigh Edmonton Cement Plant, located in Edmonton, AB, Canada
Source: Lehigh Cement

ABOUT THE INTERNATIONAL CCS KNOWLEDGE CENTRE

Founded in 2016 as a non-profit organization by BHP and SaskPower, the Knowledge Centre is dedicated to advancing the understanding, the application know-how, and the use of large-scale CCS as a means of managing GHG emissions. The Knowledge Centre is unique in that it houses experts who were instrumental in the development and operations of the BD3 CCS Facility. Understanding the full-chain realities and complexities of a deployed, world-leading project, the Knowledge Centre offers insight into practical deployment considerations. The Knowledge Centre places a high value on information and expertise that is permitted to be broadly shared with multiple parties. This promotes research, innovation, and deployment by reducing the cost and risk associated with new CCS projects in Canada and around the world.

The Knowledge Centre's technical advice for planning, design, construction, and operation of large-scale applications of CCS is applicable directly to project developers seeking to de-risk investment decisions through informed due diligence. The team also actively engages financiers and decision makers to ensure high-level information on CCS is conveyed with political, economic, and other broad considerations. The Knowledge Centre staff are experts that can be relied on to aid in developing roadmaps for CCS considerations and providing strategic and business case advise along the path to deployment.

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NECESSITY OF CCS ON CEMENT

Global population expansion, increased urbanization, and economic and social development underpin a continued strong demand for key industrial materials. Concrete, a mixture of cement, aggregates, water, and specialty additives is the second most consumed substance on the planet, next only to water - attributing roughly 3 tonnes of concrete to every person on earth annually.[2] The carbon footprint ranges from approximately 700-800 kg of CO_2 per ton of clinker produced to 500-700 kg of CO_2 per ton of cement produced.[3]

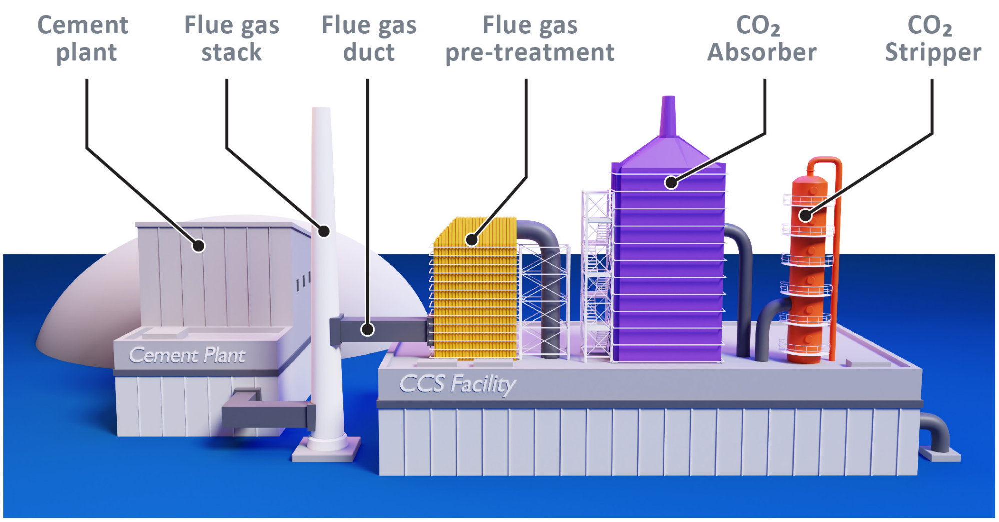
Globally, more than 4 billion tonnes of cement are produced on an annual basis, leading to a total emissions profile from the cement industry of 7-8% of global anthropogenic CO_2 emissions.[4] With global demand for cement expected to increase 12-23% by 2050, there is a drive to create low carbon footprint cement products as sustainable building materials.[5] In fact, much of the cement and concrete industry is developing principles from the United Nations Sustainable Development Goals (UN SDGs) in managing their social, environmental, and economic impacts. It is recognized that by providing affordable, durable, and resilient concrete for vital infrastructure and housing, the industry is well-positioned to contribute a critical resource in achieving many of the UN SDGs.[6] The Global CCS Institute also notes that CCS is an essential, and cost-effective step towards net zero for the cement industry given the limited decarbonization options available.[7] Additionally, the Intergovernmental Panel on Climate Change (IPCC) has recognized that CCS will have to play a major role in decarbonizing industry sectors with higher process emissions such as cement.[8]

As noted and distinct from the energy sector, where power production can advance toward the integration of renewable and alternative fuels, in the cement production process only one-third of emissions[9] come from energy requirements. Those combustion emissions can be reduced; however, the remaining two-thirds of CO_2 emissions are unavoidable industrial process emissions from the production of clinker. Currently, there is no feasible method to reduce these, hence carbon capture plays a vital role for reducing CO_2 emission for cement.

With an aim to achieve carbon-neutral concrete by 2050, the Global Cement and Concrete Association (GCCA), developed roadmaps that set clear paths for the cement and concrete sector to achieve this goal using a circular economy approach. Coupled with a variety of strategies to shrink the carbon footprint across the manufacturing and usage chain, there is a desire among the collective to see a significant reduction of process emissions through technological innovation, and with the addition of large-scale carbon capture technology.[10]

The World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD) developed the GHG Protocol, which is a standard globalized framework to measure, manage, report, and reduce GHG emissions from public and private sector operations.[11] The protocol's scope 1, outlines the role carbon capture plays in reducing emissions associated with fuel combustion and process emissions in the manufacturing of cement. The protocol's scope 3, describes how the use of CCS during the production of cement, benefits the entire cement and concrete construction value chain and ultimately reduces embodied carbon in the built environment.

Figure 1: Components of a Cement Processing Facility Connected to a Carbon Capture Facility



Post combustion flue gas from cement processing is remarkably similar to that of coal thermal plants. Lessons learned, course corrections and advances in carbon capture technology are readily adapted and transferred across industries.

Source: International CCS Knowledge Centre

The host municipality for the feasibility study, the City of Edmonton, recently became the second Canadian city to create procurement policy centered on the use of construction materials with lower embodied carbon[12] Edmonton's policy states that all new municipal building construction must consider using material with the lowest embodied carbon or an otherwise equivalent material. Cement produced with a carbon capture facility aids the concrete construction market, to expedite the reduction of embodied carbon in Alberta's and Canada's construction sectors and demonstrate global leadership in sustainability.

VALUE OF LESSONS LEARNED

Widespread deployment of CCS technologies is essential for successfully tackling climate change which requires knowledge sharing by first-movers. Early adopters such as the SaskPower BD3 CCS Facility and Petra Nova coal-fired power CCS projects have assumed the risks and costs associated with their first of a kind projects. Sharing lessons learned provides a powerful method of accelerating ideas for improving work processes, operation, quality, safety, and cost-effectiveness. For capital-intensive projects such as CCS, utilizing these fundamental building blocks can create efficiencies and help drive down costs through iterations.

Emissions from a coal-fired power plant are in many ways similar to those from other industrial sources of emissions, therefore the critical lessons learned from post-combustion CO_2 capture on coal pave the way for other industrial applications.

CCS can be applied to industrial sources of emissions, such as iron, steel, and cement, which have limited abatement options. For some industrial and fuel transformation processes, CCS is one of the most cost-effective solutions available for large-scale emissions reductions.[13] As such, strengthened and tailored policy responses will be needed to support the transformation of industry consistent with climate goals while preserving competitiveness.

With no large-scale CCS facilities currently operating on a cement plant, understanding commonalities with previously deployed CCS facilities from other sectors is necessary.

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

KEY LEARNINGS FROM THE LEHIGH CCS FEASIBILITY STUDY

ENVIRONMENTAL BENEFITS – CCS TECHNOLOGY

A cement plant of this size has the opportunity to capture up to 780,000 tonnes of CO_2 per year. The annual CO_2 emissions of a cement plant vary due to clinker production rate, market demand, and the type of fuel being consumed. The CO_2 capture plant will require an auxiliary boiler but the capture plant would be designed to capture 95% of the additional CO_2 produced by this boiler.

Amine Post Combustion Technology

When applying post combustion carbon capture technology (whether on coal or cement), the process involves scrubbing (cleaning) flue gases (emissions) using a solvent (called an amine).

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 analysis completed for the Lehigh Edmonton CCS Feasibility Study by the capture technology vendor, MHI, shows that up to 95% CO_2 capture rate is possible for this project.

Removing Pollution

In addition to capturing CO_2, a CCS project can result in environmental benefits related to other air pollutants. Operating experience 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 which will 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. At the BD3 CCS Facility, the flue gas emitted from the stack as designed when the capture plant is in operation, shows a significant improvement in the quality of all air emissions compared to its pre-retrofit emission performance.[16]

In the Lehigh Edmonton CCS Feasibility Study, the overall result of reduction in pollutants beyond CO_2 has been to substantially reduce emissions of Sulfur Oxides (SO_x) and particulates., while Nitrous Oxide (NO_x) emissions continue to stay well below Alberta Ambient Air Quality Objectives (AAAQO)

The amine-based post-combustion carbon capture technology application identified during the feasibility study and selected for the Lehigh Cement plant has a technology readiness level (TRL) of 9 on a scale from 1 to 9. The TRL index, originally developed by NASA, describes the maturity of technology.[14] A technology with a TRL 1 spans concept studies and very basic technological research. A TRL 9 usually describes a technology that is tested and qualified for deployment at industrial scale and is fully operational under normal commercial services. The Global CCS Institute surveyed the technology readiness of both mature and emerging technologies in the capture, transport, and storage of carbon dioxide.[15]

With a rating of TRL 9, the carbon capture technology chosen for Lehigh Cement Plant, means that it is proven through successful deployment in an operational setting (in this case, thermal power generation.). However, since the integration this technology into a cement manufacturing operation is novel, the TRL is reduced to 8.

Figure 2: Emission and Air Pollutant Reductions Design Performance with use of Carbon Capture on SaskPower's Boundary Dam Unit 3

CONSTITUENT	PRE-CCS	POST-CCS*	CHANGE
Power	139 MW	120 MW	13.6%
CO_2	3604 tonnes/day	354 tonnes/day	90%
SO_2	7 tonnes/day	0 tonnes/day	100%
NO_x	2.4 tonnes/day	1.05 tonnes/day	56%
PM_{10}	190 kg/day	15 kg/day	92%
$PM_{2.5}$	65 kg/day	7 kg/day	70%

The design values for the carbon capture plant at BD3 CCS Facility demonstrated the significant reductions in carbon dioxide (CO_2) as well as Sulfur Oxides (SO_x), Nitrous Oxides (NO_x) and particulate matters.*

Source Publication: Integrated Carbon Capture and Storage Project at SaskPower's Boundary Dam Power Station. SaskPower & IEA Greenhouse Gas R&D Programme (IEAGHG)

Having a low-carbon footprint can add economic value to cement. Capturing and sequestering CO_2 from a cement plant can create a product that is in high demand through green procurement practices.

Green Infrastructure

Concrete can help to provide the foundation for climate-resilient infrastructure. Commitments in this area are already being pursued in large multi-national corporations in a bid to accelerate the push to meet climate goals and help develop greener supply chains.[17] Aiding this push for greener building materials, Canada's cement and concrete industry have taken strides to be a competitive global leader in the production of, and technologies related to low-carbon cement and concrete.[18]

Having a low-carbon footprint can add economic value to cement. Capturing and sequestering CO_2 from a cement plant can create a desirable product for domestic and export markets due to the growing demand through green procurement practices. This not only results in low-embodied-carbon concrete, but infrastructure which is durable and will exhibit long-term climate resilience for generations to come.

SITE CONSIDERATIONS

The existing cement plant for this feasibility study is located in an urban setting and already uses the majority of the available footprint. The addition of a post-combustion carbon capture plant in this situation presents challenges for navigating limited placement options for new facilities, while also trying to ensure there is minimal impact on cement operations. Available space has had to be considered for the permanent plant as well as for cranes and module staging, and cold and heated storage.

Having a metropolitan location may warrant consideration for water vapor plume visibility. Even though the emissions from a capture plant lie within regulatory emissions limits, a visible plume may raise questions from the public as to why emissions appear to be going into the air. To mitigate the plume visibility, a cooling system can be used with plume abatement, in addition to other potential design adjustments. There is also potential for the moisture to produce ground level fog that could affect visibility on major roadways, as well as at the capture plant itself.

Another consideration for being located in Edmonton is that ambient temperatures fluctuate significantly between -45°C to +35°C in the winter and summer months, respectively. These ambient temperatures may affect certain design aspects of a facility and may require portions of the facility to be located indoors to prevent freezing or facilitate maintenance.

Permitting

CCS projects can face a complex and time-consuming permitting process, with requirements varying by jurisdiction and location. It is important to know the permitting requirements of a project, and once a final selection of the capture plant footprint is determined, the development of permit applications and advanced coordination with regulators is required. Permitting considerations related to an Environmental Impact Assessment (EIA), anticipated environmental permits, and emission thresholds for amine and amine degradation products were considered as part of the Lehigh Edmonton CCS Feasibility Study.

Analyzing all emissions from a host facility and the additional components required to operate carbon capture at site are required. This includes certain pollutants and air toxins such as amine. The post-combustion carbon capture process involves the contact of amine with the flue gas and aerosols in the flue gas can lead to the formation of a very small amount of fine amine droplets which are expected to be released into the atmosphere along with the cleaned flue gas. As evaluated in the Lehigh Edmonton CCS Feasibility Study, the marginal release of amine into the atmosphere would not result in exceedances of current air quality and emissions regulations.

Figure 3: Potential Siting of the Lehigh Edmonton CCS Facility

As a carbon capture facility requires a sizable footprint, site characteristics and minimal impact on operations are major considerations in determining location. The above illustration shows one of the proposed options for siting a carbon capture facility at the Lehigh Edmonton Cement Plant

Source: International CCS Knowledge Centre

INTEGRATION

Finding Energy

The main challenges of post-combustion CO_2 capture are the amount of thermal energy required when the solvent undergoes a process called "regeneration" and for the mechanical energy to drive the CO_2 compressor (either thermal or electric). Thermal energy may be accessed from the host facility (in the form of existing waste heat if available) or from an additional dedicated steam supply. The use of waste-heat in the Lehigh cement plant to generate steam for the CO_2 capture plant was investigated through this feasibility study and it was determined that there is not sufficient heat energy available for it to be economically feasible for the project.

With access to waste heat eliminated as an option, the project requires the addition of an auxiliary boiler for supplemental steam supply. A potential economic enhancement (to be further evaluated during FEED) is to substitute a combined heat and power (CHP) or co-gen system instead of the auxiliary boiler. For the Lehigh application, early technical work identified the potential for up to 80-100 MW of power generation, reducing the cost of electricity through self-generation while creating an additional revenue stream through partial grid power displacement and/or excess power sales into the grid.

Compressor driver selection (steam or electric) was also evaluated during the feasibility study. Preliminary results suggest that a steam driven compressor in conjunction with the above mentioned CHP enhancement would produce the best economic result while also minimizing the incremental CO_2 emissions associated with CO_2 compression. Detailed evaluation of how heat and steam can be more efficiently used and combined will be examined in the FEED study.

Cooling

Capturing CO_2 with amine works better at low temperatures. During the Lehigh Edmonton CCS Feasibility Study, an innovative hybrid cooling option was selected to eliminate excess heat generated in the capture plant.

Since the temperature of the flue gas from a facility is quite high, a significant amount of heat must be removed. However, moisture in the flue gas condenses as it is cools creating a condensate byproduct. In order to prevent an undesirable wastewater stream, this feasibility study examined an option to repurpose the condensate for wet cooling.

The hybrid cooling system is a combination of wet and dry cooling. The wastewater from the cooling system and the process can be used in the existing cement facility, eliminating the need to dispose of this wastewater while reducing the amount of fresh water the plant requires. The remaining heat would be cooled by dry cooling, mostly performed by fans.

OPERATING CAPACITY & AVAILABILITY

Operating Capacity

Capture plants are most often designed to run at the maximum operating capacity of the host facility. As explained in the Shand CCS Feasibility Study (on a 300 MW coal plant), power plants run at variable capacity based on the demand for power from the plant which fluctuates throughout the day, month, and year, or to accommodate an increase of renewable energy coming online. This fluctuation in power output creates challenges for a capture plant to react to the corresponding fluctuations in flue gas, as well as the associated chemistry changes that result from the variations.

Unlike a power plant, industrial facilities, such as cement, run at almost full production when in operation allowing for more stable, predictable operation of the capture plant.

Availability

Another difference between power and cement plants is the amount of time in operation. This can be referred to as its 'availability' to provide CO_2 to the capture plant. A power plant, strives to operate over 90% of the time, this helps the cost per tonne of capture. For a cement plant, operating time is subject to inventory, market demands, and other factors which can fluctuate through the year, and thereby impact the level of its availability. In general terms, the availability of cement plants is lower than power plants, resulting in a higher capture cost per tonne.

DESIGN IMPROVEMENTS

Amine Health

Every amine solvent behaves differently from one combustion source to another due to the differences in amine chemistry, and the composition of the flue gas stream. In the presence of the common components and undesirable particulates present in a flue gas stream, amines degrade over time and must be supplemented with fresh amine solution for the capture process to continue optimally; this replacement can increase operating costs.[19] Degradation products and operational challenges are unique to each of the different amines in combination with the properties of various flue gas streams.

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 solvent. To combat these concerns, flue gas pre-treatment, a high level of redundancy, and equipment isolation should be included to ensure the capture plant operates reliably with minimal downtime or amine degradation.

Filtration equipment was included in the Lehigh Edmonton CCS Feasibility Study to achieve continuous removal of particulate matter to reduce the potential for accelerated amine degradation and fouling (i.e., unwanted deposits causing issues) in the CO_2 removal equipment.

Redundancy & Isolation

In the Lehigh Edmonton CCS Feasibility Study, redundancy and isolation were applied to selected systems that are vital to the plant's reliability based on the BD3 CCS Facility design and operating experience. Redundancy was added to equipment critical to maintaining continuous process operations or for equipment susceptible to frequent fouling. Isolation was also included to allow online maintenance or cleaning of fouled equipment. While the addition of redundancy and isolation increases capital cost estimates; they also act to minimize shutdowns of the carbon capture plant and future maintenance costs, improving reliability and reducing LCOC.

RESULTS, ECONOMICS & OTHER CONSIDERATIONS

LEHIGH EDMONTON CCS FEASIBILITY STUDY FINDINGS

After incorporating all of the above learnings, as well as accounting for various site-specific factors, the Lehigh Edmonton CCS Feasibility Study produced AACE Class 4 capital expense (CAPEX) and operating expense (OPEX) estimates.

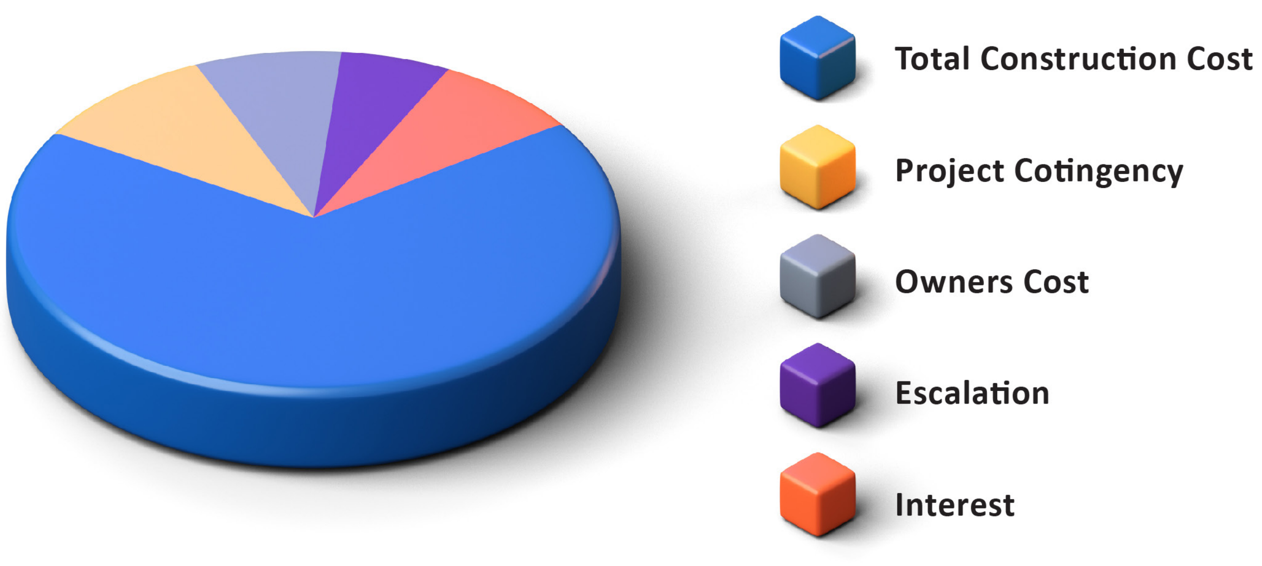
CAPEX and OPEX

The total CAPEX estimate for the Lehigh CCS project was determined to be just over **CDN**$640M at the feasibility stage, including base construction costs and excluding contingency, escalation, interest and other owner's costs. The CAPEX estimate does not include any scope outside of the fence line (i.e., transportation or sequestration of CO_2). As can be seen in the chart below, the construction cost of the CO_2 capture and compression plant along with the balance of plant make up most of the CAPEX.

Constructing a CCS facility and integrating it into another facility is expected to include large and expensive parts that can be made directly in Edmonton. Such modularization will reduce costs and time on site and will contribute to Edmonton's manufacturing sector.

The economic impact of such manufacturing is significant, with further multiplier impacts throughout the regional economy as these funds are expended. A 15% contingency allowance was deemed appropriate for this stage of the project and was added to the base construction costs.

Figure 4: Breakdown of Capital Expense (CAPEX) Estimate

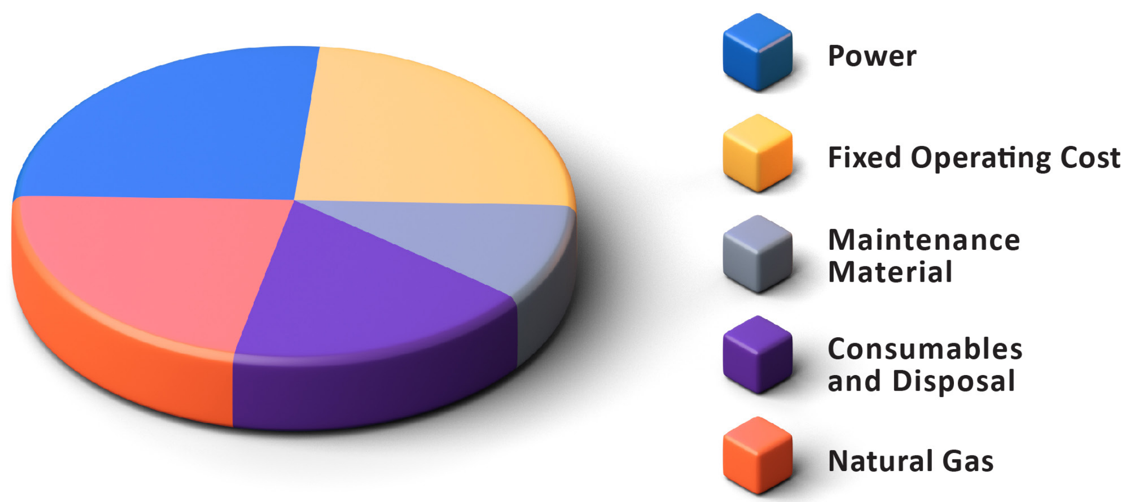


Breakdown of Capital Expense (CAPEX) Estimates presents a +/-20% cost range for the project (AACE Class 4)

Source: International CCS Knowledge Centre

The annual OPEX was estimated to be just over **CDN**$36M including fixed and variable operating costs. The fixed operating costs include elements like labour, taxes, and insurance. As can be seen in the chart below, about 50% of the annual OPEX cost is related to the cost of natural gas and electricity. The remaining OPEX costs are related to annual maintenance and the cost of consumables.

Figure 5: Breakdown of Operating Expense (OPEX) Estimate



Breakdown of Operating Expense (OPEX) Estimates presents a +/-20% cost range for the project (AACE Class 4)

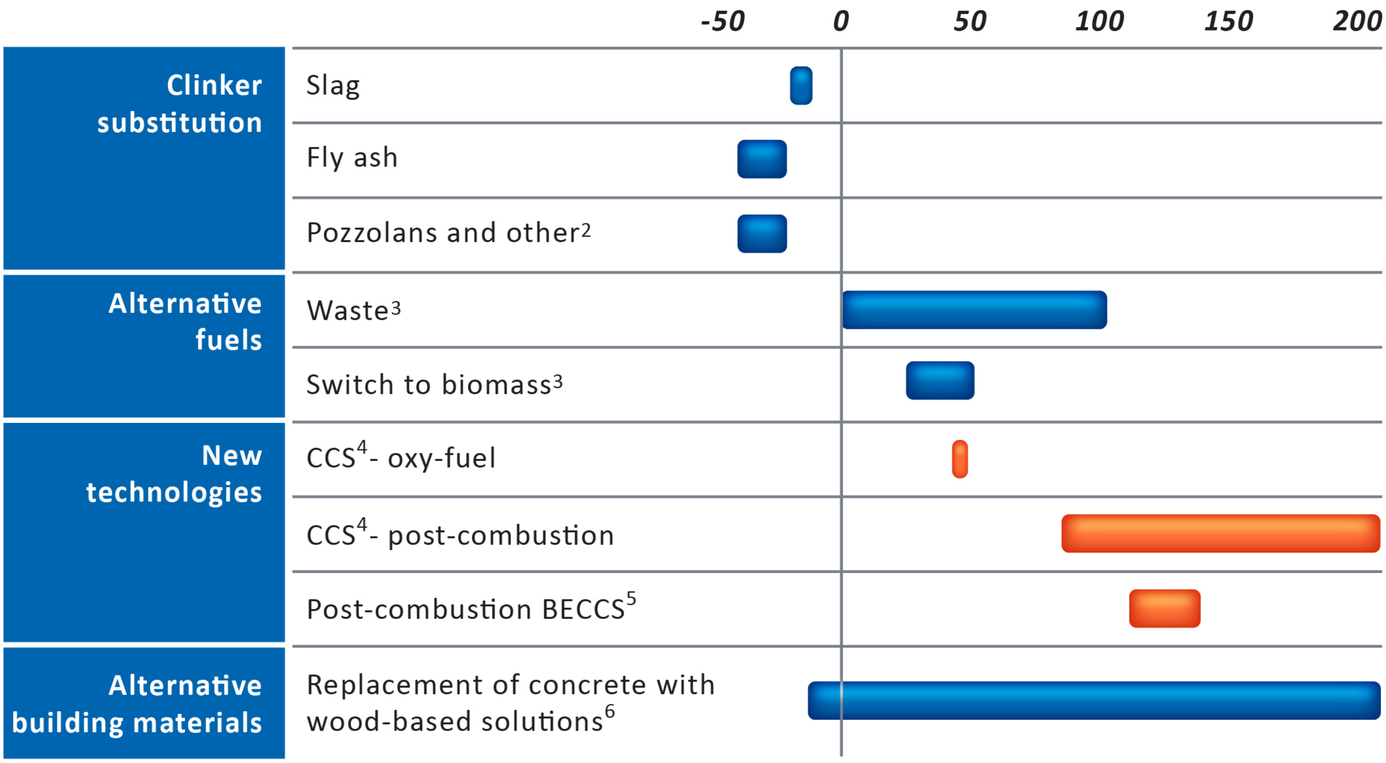
Source: International CCS Knowledge Centre

Levelized Cost of Capture (LCOC)

The levelized cost of capture is a standard industry approach to illustrate the cost per tonne of CO_2 captured. It represents the ratio of the net present value of CAPEX and OPEX to the net present value of the CO_2 captured over the life of the facility. This factor is used to compare the relative value of different potential CCS projects.

A study by McKinsey and Company (McKinsey) assessed various ways to decarbonize cement, with post-combustion CCS ranging from just under **USD**$100/t$CO_2$ to around **USD**$200/t$CO_2$.[20] The Lehigh Edmonton CCS Feasibility Study estimates the cost of capture of up to 780,000 tonnes/yr to be well within this range.

Figure 6: Cost Comparison for CO_2 Abatement in the Cement Sector ($/t$CO_2$)



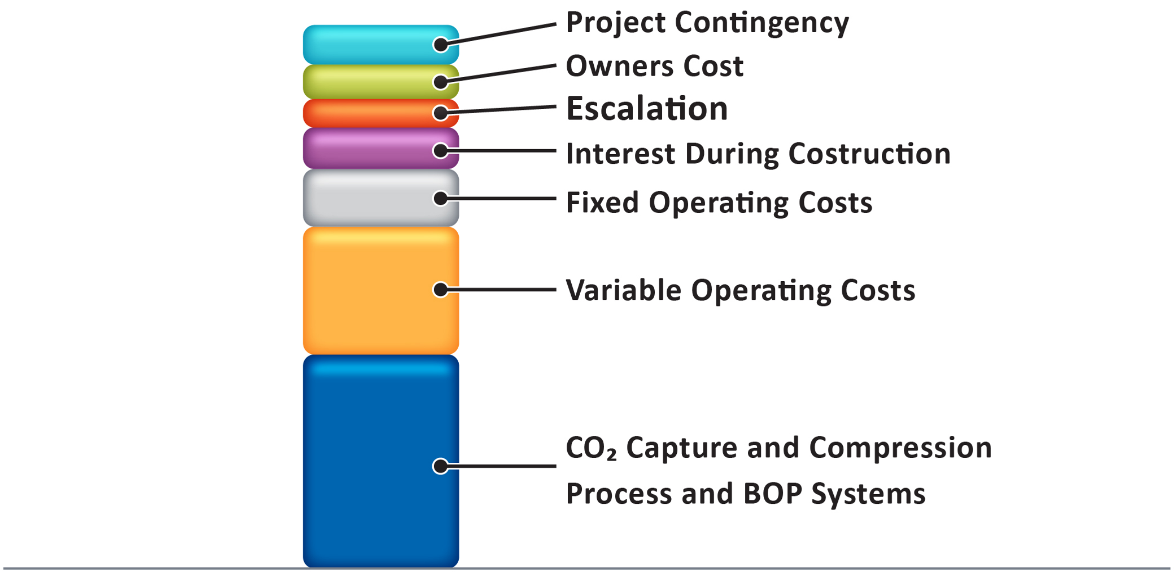
1 Globally assumed cost, can vary locally.
2 Limestone, kaoline and other.
3 Depending on availability, quality of material and cost to dispose.
4 Carbon capture and storage.
5 Bioenergy with carbon capture and storage.
6 Includes abatement coming from displacement from steel.

Source: McKinsey & company (2020). Laying the foundation for zero-carbon cement.

A chart showing the contribution of the CAPEX and OPEX components to LCOC follows on the next page. CAPEX accounts for approximately two thirds of the LCOC.

Norcem Brevik Cement Plant, (part of the Heidelberg Cement Group) located in Brevik in Telmark, Norway.
Source: Norcem Brevik

Figure 7: Breakdown of Levelized Cost of CO_2 Capture



The Net Present Value of the costs associated with the capture process divided by the net present value of the CO_2 captured.

Source: CCS Norway (2020), All rights researved.

COST REDUCTION OPPORTUNITIES

To improve the financial performance of the project, the feasibility study identified a number of factors that should be examined further during a FEED study to ensure that the final design is optimized prior to a final investment decision. These include the amount of flue gas pre-treatment, and the implementation of combined heat and power.

Flue Gas Pre-Treatment

With capture on a cement plant being a new opportunity globally, understanding how cement flue gas reacts with the post-combustion process requires certain precedent assumptions from other capture facilities. In a conservative effort to ensure minimal amine degradation, the Lehigh Edmonton CCS Feasibility Study included a high level of flue gas pre-treatment. Further stack testing to evaluate the composition of the existing flue gas at the cement plant may allow for reduction of pre-treatment costs.

Combined Heat & Power

Powering a capture facility requires considerations for the cost of energy like electricity and natural gas. For the Lehigh Edmonton CCS Feasibility Study, approximately 50% of the annual operating costs are associated with additional power for the capture facility. Considerations for steam were highlighted above, but a key finding of this study is that there can be efficiency gains available by generating electricity and steam rather than just generating steam for the CO_2 capture process. As such, the addition of a "combined heat and power" system is recommended to be connected to this project to significantly reduce the cost of electricity for the capture plant, while potentially allowing excess electricity to be marketed to the Alberta Energy System Operator (AESO) for additional offsetting of costs through generated revenue and additional environmental attributes.

GOVERNMENT SUPPORT

Permanent & Safe Storage

Alberta's strategy to create carbon hubs and the pore space tenure process will provide access to shared infrastructure. Key elements of this strategy are likely to include fair fee-for-service in return for full flow of credits back to the capturing project.

Grants, Incentives & Financing

Post-combustion capture CCS projects are large-scale, capital intensive projects that are currently not financially accretive to the shareholders of any large industrial emitters including cement. Direct evidence of this lies in the history of virtually every existing large-scale CCS project across the globe to date receiving significant government support.

Given the need to accelerate deployment and create the large-scale emissions reductions necessary to make progress against stated targets, Governments will continue to be "partners" and contribute to progress through development of policy, regulations, and programs that ultimately help to de-risk and support the business case such that CCS projects receive positive final investment decisions (FID) and proceed.

In Canada, there are a myriad of existing and developing policies, regulations and programs at both the provincial and federal levels designed to incent and or support decarbonization strategies including development of large-scale CCS projects.

Examples include: the Carbon Tax, Clean Fuel Standard, Alberta TIER Program, the recently announced Investment Tax Credit(ITC), Strategic Innovation Fund(SIF), ERA FEED funding call, Alberta Petrochemicals Incentive Fund, Federal Energy Innovation Program (Carbon Capture, Utilization and Storage Stream), etc.

CCS project developers must have an in-depth understanding of CCS policy, regulation and all the support programs and emissions credit generation mechanisms and how they do or do not work together to support the overall business case.

Additionally, the Canadian Infrastructure Bank (CIB) may be available to provide low-cost financing to projects that can clearly demonstrate a contribution to long term, material reductions to Canada's CO_2 emissions.

JOB CREATION

In addition to the environmental benefits that stem from this project, implementation of a large-scale CCS project at the Lehigh Cement facility will provide Albertans with measurable economic stimulus in the form of job creation and related spending. CCS projects deliver 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 5 million person hours of work on-site during construction for both the CCS facility and the power plant upgrades for retrofit.

For the Lehigh Edmonton CCS project, given its proximity to manufacturing capabilities in the Edmonton area, a higher level of modularization can be expected for the project. This, in combination with the fast-tracked construction timeline expectations and lessons learned for various aspects, puts the Lehigh project estimate at over 2-million-person hours of direct employment during the construction phases and over the life of the project a total economic impact of **CDN**$900M in GDP. 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.

DRIVING FUTURE OPPORTUNITIES

PUBLIC PERCEPTION

It is increasingly recognized that public acceptance of CCS is a vital precondition for accelerated deployment. For example, the IEAGHG Weyburn-Midale CO_2 monitoring and storage project in Saskatchewan has been operational for over 20 years and included large public engagement. To date, the project has sequestered over 36 Mt of CO_2, and is widely accepted and understood.

The Canadian geological landscape has the capacity for a large volume of permanent and secure CO_2 storage, and the government has a role to play in regulatory expectations. Canada is a global leader in CCUS, so international knowledge-sharing could enhance its competitive advantage and play an essential role in the transition to a prosperous net-zero economy. Given the understanding gained from years of oil and gas expertise, and the rigorous measurement, monitoring, and verification required, along with provisions for long-term liabilities, public perception of these projects can be positive.

Furthermore, first-mover projects like Shell Quest and the BD3 CCS Facility have been proven and in operation for several years. Such projects show the public that CCS is possible, it is safe, and that it works. These world firsts have paved the way for building public confidence.

For example, many rural locations are supportive of having CCS in their community as they recognize the substantial benefits such projects bring, such as job creation and economic stimulus. The positive contributions that CCS can play for post-COVID stimulus, climate action, and building back better can bolster the public narrative. Such large infrastructure and construction projects require highly skilled personnel and transferable skills that can be put to work in short order. With the number of job losses in the oil and gas sector that are transferable to CCS projects, this creates a transformational opportunity to leverage this knowledge and experience base and steer workers to future-focused career opportunities that will be part of world-leading innovation and development.

Furthermore, Environmental, Social and Governance (ESG) consideration for capital markets has gone from an aspirational activity to a mainstream, essential aspect of commercial behaviour in recent years. Climate change is now synonymous with the 'E' in the acronym, making a corporation's exposure to climate-related risks central to ESG. Virtually all decarbonization scenarios assume material use of CCS in the future, which is why upscaling CCS is so important. Deploying proven solutions that significantly reduce emissions, build communities, and continue to contribute to a more sustainable future is a global prerogative.

KNOWLEDGE TRANSFER

As a first-generation CCS plant on a cement facility, there is an inherent opportunity to export knowledge from the project's design, construction, and operation to ensure a cascade effect to accelerate deployment and reduce costs in this sector. The lessons learned to adapt large-scale CCS to the unique challenges of a cement manufacturing facility will be invaluable to advancing the global understanding of and business case for the application of CCS technology tomorrow.

Successful completion of a commercial scale capture facility at the Lehigh Edmonton cement plant could accelerate the technological and economic case for applying large-scale CCUS across countless other hard-to-abate sectors, significantly multiplying the economic and environmental benefits of the project. This assertion is supported by global assessments that identify cement and concrete as among four keystone sectors for unlocking a **USD**$800B market for CCS technologies.[21]

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