Final Outcome Report

Non Confidential

Prepared for Emissions Reduction Alberta

Project Title: Multi Site Cement Industry Low Carbon Fuel Implementation and Supply Chain Optimization

Project ID: B0162016

Project Advisor: Jennifer Chen

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Completion Date of the Project: May 31-2022

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Technology Readiness TRL at project Initiation: N/A

TRL at Project Completion: N/A

Total Actual ERA Funds Received: $79, 274.88

Total Actual Project Costs Including a Breakdown of Total Eligible Costs and Total Ineligible Costs:

	University of Calgary				Queen's University		
	ERA	**Lafarge**	**AITF**	**NSERC**	**OCE**	**Lafarge**	**NSERC**
Eligible Costs							
Salary & Benefits	**$127,822.41**	**$87,008.40**	**$110,951.81**	**$138,546.43**	**142,843.65**	**65,125.5**	**$84,245.65**
Consulting-Subcontracting	**$17,419.11**	**$--**	**$62,591.67**	**$17,345.73**	**$--**	**$--**	**$--**
Materials & Supplies	**$4,758.48**	**$1,377.24**	**$4,261.31**	**$320.20**	**1,033.94**	**6,767.21**	**35,734.55**
Travel	**$--**	**$--**	**$4,763.95**	**$8787.64**	**6,122.41**	**3,107.29**	**$--**
Other	**$--**	**$4,114.36**	**$--**	**$--**	**$--**	**$--**	**$--**
Total Eligible	**$150, 000**	**$ 92,500**	**$ 185, 000**	**$ 165,000**	**$ 100,000**	**$ 92,500**	**$ 120,000**
Total Ineligible	**$ --**	**$ --**	**$ --**	**$ --**	**$ --**	**$ --**	**$ --**
Overhead	**$ --**	**$ --**	**$ 37,000**	**$ --**	**$ --**	**$ --**	**$ --**
Total	**$150,000**	**$92,500**	**$222,089**	**$165,000**	**$195,000**	**$75,000**	**$120,000**

Executive Summary

The cement industry plays an important role in Canada's infrastructure and green building ambitions. While the industry is an innovative contributor to a low carbon future, it is also a large emitter of CO_2 and contributes 3.8% of national GHG emissions. LafargeHolcim Canada has undertaken a pathway toward achieving a lower carbon fuel (LCF), as well as identifying technology pathways to achieve even lower carbon footprints associated with cement production. To accomplish this goal, the researchers at the University of Calgary and Queen's University embarked on a research project to identify alternative fuels (AF) and technologies that can help Lafarge lower their carbon footprint.

Physical and chemical properties are important factors for selecting an AF. An example is moisture content. Dry materials are prone to ignition and explosion in the storage, whereas wet materials are prone to conglomeration, clogging of the delivery channels, and reduction in the caloric value. As part of this project, Queen's University has developed a multilevel drying apparatus to test various materials' drying regime. Understanding AFs' drying properties using first principles is not possible due to their complex nature; however, the results of routine tests on the optimal drying regime of various materials can be used to adjust the actual drying regime of the materials, and to optimize the waste heat recovery from the kiln.

Dust explosion is another factor that was studied in this project. Processing, handling, storage, and use of AFs in a cement facility generate dust that presents an explosion hazard when suspended in air and when fuel, ignition source, dispersion, confinement, and oxidant are present. When studying a dust explosion, dust properties (particle size, moisture content, porosity, concentration), and processing conditions (type of ignition sources, turbulence) should be considered in addition to explosibility parameters p_{max} and k_{st}. Recommendations were developed in this study to minimize dust explosion incidents based on the dust properties, the location of explosions, and the explosion pentagon. Among the recommendations are prevention of heat conduction from kiln to feeder, eliminating tramp metal to avoid sparks of friction, increasing particle size and moisture content, and avoiding dust accumulation and ignition sources.

This project also included development of Excel-based LCA models to understand the impact of AFs on GHG emissions and criteria air contaminants (CAC) by assessing impacts of scenarios such as replacing NG with AFs, biogenic global warming potential factors (GWP_{bio}), supplementary cementitious materials (SCM) in concrete, and carbon capture and storage (CCS) strategies in cement and concrete sector. The AF mixture considered in the base case of the LCA model includes construction and demolition waste. Railway ties, asphalt shingles, tire fluff, carpet/textiles, and plastics. The system boundary includes various life cycle activities including resource extraction and processing, energy consumption, and transportation logistics. The results of the LCA show when 50% energy content of NG is replaced with the AF mixture, the emissions increase by up to 13% or decreases by 3.9% depending on the GWP_{bio} assigned to the AFs. Calcination of raw materials to clinker contributed to 66-79% of emissions. SO_X and particulate matter emissions remain the same. NO_X emissions decreases in the AF scenario due to the decrease in the reaction temperature.

A numerical model was developed using the OpenFoam CFD software that is focused on comprehensive physical and chemistry modelling of coal combustion, advanced devolatilization for particle gasification inside the combustion chamber, NOx production modelling, and a two-phase aerodynamics model of fuel particles. To overcome poor modelling of devolatilization in the existing software, advanced numerical tools were developed that are capable of modeling movement, evaporation, chemical reaction, and heat transfer of individual fuel particles by obtaining realistic conditions recorded in the kiln operations using coal. The results can readily be utilized to inform LCF trials.

A thermal energy flow model was developed for a 4,200 tonnes clinker/day cement plant to assess its performance after substituting 50% NG by AF. The results showed that the replacement without changing the [O_2] has little impact on thermal energy intensity (TEI) and air demand (AD). Increasing [O_2] from 1% to 3% increases the average TEI, AD, and GHG emissions by 13%, 21%, and 9.3% respectively, relative to the NG-based plant with 1% [O_2]. The use of carbon-neutral AFs such as wood dust at 3% [O_2] in the flue gas could avoid GHG emissions by 5.8%. Non-biogenic waste-derived fuels such as high-density polyethylene (HDPE) could increase GHGs by 5.5%.

A techno-economic assessment was performed on the oxy-combustion of the fuel in the kiln, coupled to a CCS unit. The results show that oxy-combustion increases both the thermal energy and electricity demand (ED), but the increase in ED is lower (67%) when electrolytic oxygen is used. The levelized cost of oxygen supply for the pipelined electrolytic oxygen was \$35/tO_2 (200 km) and \$13/tO_2 (20 km), comparing to \$49/tO_2 for an on-site air separation unit (ASU). The cost of clinker for the plant without CCS increases from \$84/t to \$193/t clinker at a carbon price of \$0/tCO_2 to \$150/tCO_2, respectively. After adding a CCS unit, the cost ranges from \$119 to \$122/t clinker, reflecting a breakeven carbon price of \$39 to \$53/tCO_2.

The impact on GHG emissions of the integrated low emission cement and power reduction system (LECAPP) by incorporating external reforming molten carbonate fuel cells to capture CO_2 emissions from a NG-fired cement plant was also studied. The hydrogen demanded by the fuel cells is generated using NG or HDPE while producing both low carbon electricity and a CO_2 stream for sequestration. The results showed that there is a 92% reduction in GHG emissions assigned to clinker production compared to a plant without carbon management. In the HDPE-based scenario, 144 kg plastics/t clinker would be diverted from landfills.

This research will provide the framework for replacing high carbon intensity fuels with AFs through evaluation of fuel characteristics and availability. In addition, by using AFs, cogeneration and other innovative technologies, the cement manufacturing industry will assure its own sustainability in a time of emerging climate change challenges.

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Project Description

1. Introduction

The cement and concrete industry plays an important and growing role in Canada's infrastructure and green building ambitions. While the industry is a strong and innovative contributor to a growing clean economy, the industry is also a large emitter of carbon dioxide. Global cement and concrete production are set to increase to over 5 billion tonnes per year due to rapid urbanization and economic development. Even though concrete and its primary precursor, cement are the most widely used building materials globally, they contribute to approximately 8% of global greenhouse gas emissions (GHGs). In Canada the industry comprises 3.8% of the national total. Carbon emissions from the cement industry arise from the conversion of limestone to lime, which releases CO_2, and from the use of fossil fuels in the thermal processes. In the Canadian cement industry over 90% of fuels used are coal, petcoke, natural gas, and other high fossil content fuels. To lower their carbon footprint, Lafarge Holcim Canada has undertaken a pathway toward achieving a lower carbon fuel (30% co-fire) rate, as well as identifying technology pathways that will make it possible to achieve even lower carbon footprints associated with cement production.

Half of the cement plants in Canada are in Alberta and Ontario, representing 60% of Canada's production. If the entire Ontario and Alberta cement industry were to achieve low carbon fuel (LCF) co-fire rates at 30% by 2020 this would result in an annual carbon saving as high as 1,000,000 tonnes of CO_2. The low carbon fuel trial was initiated in Lafarge's Bath cement plant near Kingston, ON. The work has been highly successful and the motivation for this project was to build on this success at additional sites in Canada, including the Exshaw plant in Exshaw, AB.

The overall objective of this project is to develop new fuel pathways to lower the carbon footprint of the cement industry. The research activities proposed to achieve this objective are:

- ❖ Measuring carbon and other air emissions and contaminants at full scale commercial operations.
- ❖ Determining alternative fuels (AF) and developing a model for selection of AFs.
- ❖ Modelling oxy combustion in clinker production.
- ❖ Studying alternative fuel dust explosivity and mitigation strategies.
- ❖ Optimizing the process of combustion by understanding the fluid dynamics.
- ❖ Developing a combustion guide for regionally viable low carbon fuels.
- ❖ Investigating carbon capture and utilization pathways and performing life cycle assessment on various pathways.
- ❖ Investigating low emission clinker and power reduction.
- ❖ Performing life cycle assessment and scenario analysis to ensure that the fuel pathways deliver the environmental benefits in efficient and cost-effective ways under a range of future policy and market conditions.
- ❖ Testing supplementary cementitious materials (SCM) and developing LCA model for manufacturing concrete containing SCM.
- ❖ Developing LCA of various pathways in concrete manufacturing.

The outcomes of this project can contribute to reduction of carbon footprint in Alberta and Canada by:

1. Allowing the cement manufacturers to select low carbon fuel that reduces their combustion emissions.
2. Helping the cement manufacturing industry to choose the alternative fuel combination that will reduce their carbon footprint without increasing the risk of alternative fuel explosion. In other words, it helps in safe transitioning from natural gas to alternative fuels.

3. Finding a method that allows permanent storage of CO_2 that is emitted during the cement manufacturing process.
4. Developing a model for the cement producing plants to evaluate the performance of their plants with various alternative fuels (AF). The model can also be used to evaluate the commercial value of AFs to Lafarge plants.
5. Finding an energy-efficient method that can capture CO_2 and co-produce low-carbon electricity for export to Alberta's grid to lower its emissions intensity.
6. Developing numerical tools capable of modelling movement, evaporation, chemical reaction, and heat transfer for individual fuel particles in the millions and obtaining realistic conditions recorded in the kiln operation using conventional fuel.
7. Developing a multi-level drying apparatus that allows effective testing of various materials with simultaneous recording of temperature, pressure, and moisture variations at six levels. The data about optimal drying regime specific to a particular material can be used to adjust the actual drying regime of the material.

2. Performance and Success Metrics

Table 1. *Performance and success metrics.*

Metric	Target	Achieved	Comments
Training (Total) M.Sc. and Ph.D. students Postdoctoral scholars Research Associates	(7) 5 2 0	(7) 3 2 2	The choice of the RA vs an M.Sc. student at the Queen's university was dictated partly by the lack of suitable candidate, partly by the project duration and partly by the dichotomy between three separate goals that would be challenging for a single graduate student to fulfill.
Publications	7	4	There are 3 publications that are currently under review or in preparation.

3. Changes during the project

One of the objectives of the project was to measure carbon and other air emissions and contaminant at full scale Lafarge commercial operations. The Lafarge Exshaw plant needed regulatory permits from the Alberta Environment and Parks to be able to burn low carbon fuels in their plant. This process took much longer than expected and this resulted in major delays in initiating and completing the research activities. Despite this the research team moved forward and worked on developing and building LCA models and decided to validate models against experimental results when the permit is in place. They obtained the permit in the summer of 2021; however, they cannot start construction of the testing facility until 2024. This task was replaced by other research activities such as exploring carbon capture, utilization, and storage scenarios for a cement manufacturing plant and their environmental impact with regards to GHG emission reduction and air contaminants, as well as studying dust explosivity of alternative fuels, and the impact of cementitious materials on concrete properties and GHG emissions. These tasks were completely in line with the initial objectives and within the scope of the project.

4. Technology Risks
There are not any particular risks associated with this project.

Project Work Scope
This project was composed of the following main research areas: 1) Life Cycle Assessment Models 2) Computational Fluid Dynamics, Laboratory studies and combustion guide, and carbon intensity factor calculations 3) System level scenario models 4) Feedstock logistics 5) Transition fuel trials at Exshaw plant.

As explained in the "Changes During Project" section, the transition fuel trials area was not completed due to regulatory permit issues. This report covers the rest of the research activities:

1. Life Cycle Assessment Models
Part of the CO_2 emissions from the cement industry are due to conversion of calcium carbonate to calcium oxide, and the rest of the CO_2 emissions and the GHG footprint is due to emissions associated with burning fossil fuels. In an effort to reduce their carbon footprint worldwide, cement manufacturers have begun replacing fossil fuels used at cement kilns with alternative fuels from landfills intending to reduce the GHG and criteria air contaminant (CAC) emissions from cement manufacturing. LCA studies have indicated up to 40% GHG and 2-23% CAC[1,2] emission reduction depending on the pollutant by replacing fossil fuels with AFs in cement manufacturing while simultaneously reducing the burden on landfills. However, this alternative fuel transition is accompanied by a set of challenges. Firstly, AFs increase the probability of dust explosions in cement manufacturing plants. Secondly, the concrete sector's GHG and CAC emissions reduction benefits using AFs in cement manufacturing are highly variable. They tend to be lower than other mitigation technologies like supplementary cementitious materials (SCM) and carbon capture, utilization, and storage (CCUS) in cement and concrete manufacturing. In addition, replacing or co-firing fossil fuels with AF can impact clinker production by changing the mass and energy flow. Below are research activities undertaken in response to some of these concerns and knowledge gaps.

Cement contributes to approximately 90-95%[3] of GHG emissions associated with concrete manufacturing. Around 50-60%[4] of cement GHG and CAC emissions are due to the calcination reaction, which cannot be altered using AFs alone. Partially replacing the cement content in concrete with an SCM like fly ash, calcined clay, etc., and capturing CO_2 from the flue gases of energy industries, storing it, or utilizing it to cure SCM-containing concrete have proved to reduce the GHG emissions associated with concrete manufacturing. However, GHG[5] and CAC[1,2] emissions reduction benefits vary for all three technologies. Even though there are abundant LCA studies available on using SCMs in concrete, very few LCA studies evaluate the impacts of SCMs on the strength and durability of concrete through a life cycle perspective.

Very few studies exist on cement facilities' carbon capture and storage deployment. Only one LCA study assesses the GHG emissions associated with the carbon capture and utilization (CCU) technique of mineral carbonation (MC) curing SCM-containing concrete[6]. The reason is that these technologies are relatively new and are yet to be commercialized. No LCA study compares various GHG and CAC emissions reduction pathways mentioned above to evaluate the trade-offs and variability of emission reduction benefits between them. Generally, individuals, stakeholders, and organizations are skeptical about alternative technologies discussed above because of the unavailability of supplementary materials, changes to existing business models, and little to no government incentives. Therefore, more insight is required to present decision-makers with the potential of sustainable alternatives to traditional cement and concrete manufacturing, which is provided by the current work.

1.1. Life cycle greenhouse gas and criteria air contaminant emissions from alternative fuel combustion in cement manufacturing (Paper 1)

This study aims to conduct a life cycle assessment to quantify and compare the GHG and CAC emissions when 50% energy content of natural gas (NG) is replaced with AF mix as kiln fuel at the Lafarge Exshaw cement plant. It also assesses the impacts of different potential treatments of the biogenic content on GHG emissions. By performing this study, we are trying to find out if substitution of natural gas with alternative fuels leads to lower greenhouse gases (GHGs) while not increasing the criteria air contaminants (CACs) emissions on a life cycle basis. In addition, we want to find out if different potential treatments of biogenic content alter these estimates.

Methods: A life cycle assessment (LCA) model is developed to evaluate the GHG and CAC emissions associated with substituting natural gas with AFs at the Lafarge Exshaw cement plant in Alberta, Canada. The fuel mixture designed by the operator will be introduced as a single component fuel; however, the dosage of the mix might fluctuate daily. This analysis informs the actual deployment of this system at the Exshaw plant. The system boundary includes various life cycle activities considered in this study: resource extraction and processing, energy consumption, and transportation. The system boundary does not include energy and material inputs for facility construction, equipment manufacture, and labor. These processes are assumed to have much smaller environmental implications than the actual operation of the facility. The LCA's functional unit is the production of 1 tonne of clinker, which occupies 95% of cement content. The life cycle inventory data, i.e., materials, energy, and emissions at each life cycle stage, was collected from an extensive literature review, various LCA databases, and interviews with plant personnel. GHG emissions included in this study were CO_2, CH_4, and N_2O, reported as CO_2 equivalents (CO_2-eq) over a time horizon of 100 years. The global warming potential (GWP) values for CO_2, CH_4, and N_2O are taken as 1, 25, and 298, respectively, based on the IPCC's Fourth Assessment Report. CAC emissions included SO_X in terms of SO_2, NO_X in terms of NO_2, and PM. Alternative fuels like wood, construction & demolition waste, railway ties, etc., have biogenic carbon. Biogenic carbon refers to the carbon sequestered from the atmosphere during biomass growth and may be released back into the atmosphere later due to biomass decomposition or combustion. Generally, LCAs treat the biogenic CO_2 emissions associated with biogenic carbon as fossil fuels and assign them a $GWP_{biogenic}$ of 1. In some cases, the biogenic CO_2 emissions are assumed to be climate neutral and given a $GWP_{biogenic}$ of 0, since the regrowing forest will absorb the CO_2 emitted from biomass combustion. This assumption is only valid if the potential sinks like the terrestrial biosphere, oceans, forests, etc. perfectly balance the carbon that is removed and is replaced by the growth of new vegetation without affecting the forest's ability to absorb carbon. In the current study, five different scenarios are modeled for the combustion of biomass-based AFs: i) biogenic carbon from AFs is considered carbon neutral and assigned a $GWP_{biogenic}$ value of zero, ii) the AFs are treated as fossil fuels and given a $GWP_{biogenic}$ value of 1, iii) $GWP_{biogenic}$ factor at which the emissions in the AF scenario are equivalent to the NG scenario, iv) $GWP_{biogenic}$ factor for the Lafarge AF mixture was calculated based on the method developed by Guest, Cherubini and Strømman, 2013.

Results: Below are a summary of our finding:

Life cycle greenhouse gas emissions for the natural gas and the Lafarge AF mixture:

1. The $GWP_{biogenic}$ = 0 scenario assumes climate neutrality, which reduces life cycle emissions by 7-9% relative to the Business as Usual (BAU) scenario.

2. In the $GWP_{biogenic}$= 1 scenario, the biogenic fraction of AFs is treated as fossil fuels and increases life cycle emissions by 3-5% relative to the BAU scenario.
3. The $GWP_{biogenic}$ factor for the Lafarge AF mixture had a negative value and was calculated based on the method developed by Guest, Cherubini and Strømman, 2013[7] . Assigning the biogenic fraction a negative $GWP_{biogenic}$ value resulted in a drop in the overall life cycle emissions by 10-15% compared to the BAU scenario.
4. The highest GHG contribution is due to the calcination of raw materials to clinker. Calcination is an endothermic reaction driven by the kiln fuels that decompose the limestone $CaCO_3$ to lime (CaO) and carbon dioxide (CO_2). This reaction and emissions resulting from it cannot be altered.

Life cycle criteria air contaminant (CAC) emissions for the natural gas and Lafarge AF mixture:
1. The oxides of sulfur (SO_X) and particulate matter (PM) emissions were estimated to remain approximately the same in the BAU and AF scenarios.
2. Out of the two kinds of nitrogen (NO_X) oxides- thermal NO_X and fuel NO_X, the oxides of nitrogen (NO_X) emissions in cement kilns are governed by thermal NO_X rather than fuel NO_X. The NO_X emissions were estimated to reduce by 5-7% while using AFs, due to the reduction in kiln flame temperature.
3. The accuracy of the calculated CAC emissions vastly depends on the completeness of the data. Although the CAC emissions calculated in this LCA study are under the permissible limits, the absence of specific data might have resulted in approximate estimates. Some of the AFs utilized in this study are new in the alternative fuel space. Hence, there is a shortage of air pollutant emission estimates from combusting novel AFs such as railway ties, natural textiles, asphalt shingles, etc., in cement kilns. This led to making certain assumptions regarding the composition of novel AFs to calculate CAC emissions. In addition, it will be helpful to compare modeled estimates with estimates collected from real-time on-site tests in the future, which could not be accomplished in this study, since the AFs could not be tested in real-time at the Lafarge Exshaw plant due to regulatory permit issues.

A Sensitivity analysis is performed by varying the alternative fuel mixture and estimating the impact on the life cycle assessment. The results are as below:
1. Construction and demolition (C&D) waste has the most extended storage period, resulting in the lowest $GWP_{biogenic}$ value for C&D compared to other AFs. Therefore, only construction and demolition (C&D) waste has lower greenhouse gas (GHG) emissions per tonne of clinker than the base case, while all the other fuels result in higher emissions.
2. The $GWP_{biogenic}$ value for the Lafarge AF mix is lower than the wood, railway ties and natural textiles because it contains C&D, which has a low $GWP_{biogenic}$ value. Therefore, even though wood, natural textiles and railway ties have a very high biogenic content they still have higher GHG emissions than the base case.

A Sensitivity analysis was performed by varying multiple factors such as $GWP_{biogenic}$ of AFs, transportation distance, Kiln's energy requirements, etc. The results show that:
1. The composition of alternative fuel mixture governs the overall GHG emissions. For instance, GHG emissions decreased by 35-40% compared to the baseline when a fuel mixture containing 100% C&D was used, as C&D had the lowest $GWP_{biogenic}$ factor. There was 18-22% increase when a fuel mixture containing 100% asphalt shingles was used, as asphalt shingles had the highest $GWP_{biogenic}$ factor. Natural gas undergoes complete combustion at 1% oxygen concentration [O_2] in the flue gas; however, when AFs are introduced in the cement kiln, it is necessary to increase the oxygen concentration in the flue gas to ensure complete combustion of the AFs. The increased oxygen concentration in the flue gas raises the air demand and flue gas volumes, increasing the electricity requirements at cement kilns by 15-

18% than in the original scenario, where only natural gas is used as fuel. The increase in electricity requirements increases the carbon intensity, which leads to an increase in the overall GHG emissions; however, the use of biomass-based AFs and the treatment of biogenic components can still help reduce the GHG emissions compared to the baseline [8].
2. The use of solar thermal energy for the calcination of raw materials is under development at cement kilns in European countries. If the Lafarge Exshaw facility were to transition to kiln fuel produced from solar thermal energy, the GHG emissions would decrease by 14-18% compared to the baseline scenario.
3. A 50% variation in $GWP_{biogenic}$, biogenic content of AFs and the selection of electricity source resulted in a decrease in GHG emissions compared to the baseline scenario.
4. The type of kiln affects the GHG emissions as the energy requirements vary for different kilns. Dry kilns are more efficient because they don't need the energy to dry, dehydrate and calcine the wet materials like in wet kilns. A decrease in GHG emissions from dry kilns is observed compared to wet kilns.

A 50% variation in the lower heating value of AFs, CO_2 emission factors from the combustion of AFs and transport distances did not considerably decrease/increase the GHG emissions from baseline.

1.2. Assessing explosibility risks and mitigation when using alternative fuels in cement manufacturing (Paper 2)

Generally, a dust explosion hazard is uncommon at cement manufacturing plants because the clinker dust generated at cement manufacturing facilities is a stable oxide and does not participate in dust explosions. Therefore, cement manufacturers and plant personnel do not typically possess dust explosion and mitigation knowledge. However, with the cement facilities transitioning from fossil fuel to AF use, combustible dust is generated while handling, storing, and using AFs, which might facilitate dust explosions if an ignition source is nearby. Therefore, assessing AF dust explosibility before its use as a kiln fuel is vital to avoid hazardous conditions while reducing the GHG and CAC emissions from cement manufacturing.

The objective of this study is to quantify the likelihood of dust explosions as an additional evaluation criterion when selecting combinations of alternative fuels for cement manufacturing. The explosibility parameters of AF dust mixtures will be determined while factoring in the dust characteristics and process conditions, utilizing the experimental standards outlined by the American Society for Testing Materials (ASTM). This study does not advance the science of dust explosions. Instead, using a case study of AF dust explosions at the Lafarge Richmond cement facility (Richmond, BC), the study will make recommendations to guide the selection of combinations of materials that will lower the probability of occurrence and severity of the resulting dust explosion. By performing this study, we are trying to understand how the likelihood of dust explosions can be incorporated into systems decision-making tools.

Methods: When AFs are used as fuel in cement manufacturing facilities, they are processed before they are stored or introduced as fuel in the kiln. The processing, handling, storage, and use of AFs generates combustible dusts such as sawdust from wood, polyethylene dust from plastics, nylon, polyester dust from carpets and textiles. Combustible dusts are particulate solids smaller than 420 μm that present a flash fire hazard or explosion hazard when suspended in air or the process-specific oxidizing medium over a range of concentrations. These dusts might participate in a dust explosion if the five conditions of dust explosion pentagon namely: fuel, ignition source, dispersion, confinement, and oxidant are present simultaneously. Explosibility parameters determine the probability and severity of dust explosions and are used to design prevention and mitigation systems. However, dust characteristics and process conditions influence the likelihood of dust explosions. Therefore, it is crucial to incorporate the effect of dust characteristics and process conditions on explosibility parameters to design robust prevention and mitigation systems for cement facilities' hazard-free operation. This study aims to provide a guide to prevent and mitigate dust explosions resulting from AFs at the Lafarge Exshaw cement plant and can be generalized to guide any cement plant interested in using AFs. However, this facility has yet to begin testing the AFs due to regulatory obstacles. Hence, the Lafarge cement facility at Richmond, British Columbia, was selected as the location for the case study for the following reasons i) the cement kiln at both Richmond and Exshaw are relatively similar, ii) the Richmond's facility has already transitioned from natural gas to the AFs, identical to the ones proposed at the Exshaw facility. The dust explosion pentagon serves as a guide to evaluate the factors contributing to a dust explosion. Hence, the first step involved summarizing the composition of AFs. This was followed by outlining the locations of feeding the AFs into the kiln and the dust explosion sites to assess the potential presence of ignition sources. The other two sides of a pentagon, namely dispersion, and confinement, were also evaluated to summarize the process conditions in the location of dust explosion incidents. The potential dust/fuels that might have contributed to observed explosions were assessed for their particle size distribution, moisture content, and explosion severity parameters - K_{st} and P_{max}, using the experimental standards outlined by (American Society for Testing and Materials (ASTM)- E1226-19. The dusts that were assessed were a mix of plastic and wood shavings. Safety measures are then recommended to prevent dust explosions.

The research in this area is still ongoing. So far, only wood fines have been evaluated for their characteristics and explosion severity parameters. However, it is crucial to assess other fuels/dusts that are being utilized as kiln fuel for their attributes (such as particle size, porosity, and moisture content) and explosion severity, as well as probability parameters (minimum ignition energy (MIE)- ASTM E 2019, and minimum ignition temperature of dust cloud (MIT_C)- ASTM E 1491-06 and minimum ignition temperature of dust layer (MIT_L)- ASTM E 2021) to provide more detailed recommendations to prevent and mitigate dust explosion occurrences at cement facilities. Four different dusts used at Lafarge Richmond: dust from construction and demolition waste, wood dust, plastic dust, and tire fibre dust, have been sent to a dust explosion testing facility. Dusts are being tested for their explosion severity and probability parameters depending on the process conditions such as ignition sources, turbulence, free fall, dust concentration while factoring in particle size, moisture content, and porosity of dusts to design appropriate prevention and mitigation techniques. After acquiring the explosion severity and probability parameter test data, a detailed dust hazard analysis (DHA) will be conducted on the dust explosion incident occurred at the Lafarge Richmond facility. The DHA will include the location of explosions (with the help of a process flow diagram), causes of explosions, identification and assessment of the particle characteristics and process conditions that might have triggered the explosions, and explosibility parameters evaluated followed by prevention and mitigation recommendations.

Results: (this project is 70% complete). The results of this study showed:

1. During the summertime, wood fines and shavings, plastic, and carpet were fed into the calciner, while the main burner was only provided with tire fluff. The dust explosions were observed at the following locations- i) Rotary airlock feeder of the Downdraft Calciner (DDC), ii) Transport screw of the In-line Calciner (ILC), iii) Rotary airlock feeder of the In-line Calciner (ILC). The fuel fed into the rotary airlock feeder fell under gravity from a height through a long chute connected to the transport screw of the ILC, where the explosions were observed. Thus, assessing the effect of dust dispersion on the explosion parameters is crucial. The following ignition sources were determined to be the most important for this study- i) radiation heat, ii) fine dust layer formation on the internal surfaces of rotary airlock feeder casing and in chutes might form dust clouds if disturbed or might smolder iii) smoldering of accumulated dust in the pockets of the feeders, iv) tramp metal pieces might create sparks, v) electrostatic discharge.

Determining potential ignition sources and process conditions will help make an inventory of the parameters that should be evaluated to assess an explosion's probability and severity. For instance, in the presence of an ignition source like radiation heat, determining the MIT of dust layer and cloud will inform the minimum temperature a dust cloud or layer can resist before it ignites.

2. The particle size distribution (PSD) results indicated that a large sample of wood fines and tire fluff was below 420 μm. In contrast, very small percentage of sample of mixture of plastics and wood shavings was below 420 μm. The moisture content of wood fines was also lower than the mixture of plastic and wood shaving sample. As the wood fines were finer and moister than PEF, they participated in the dust explosions compared to the mixture of plastic and wood shavings. However, tire fluff did not participate in dust explosions even though it was finer since it was not fed under gravity. The explosibility parameters that address the severity of explosions were determined for the mixture of plastic and wood shavings, using ASTM's experimental standards (ASTM E1226-19). Both literature and actual experiment results indicated that K_{st} and P_{max} values increased with the decrease in particle size of dust.
3. Detailed long-term and concrete prevention and mitigation systems will be recommended after conducting experiments on different AF dusts.

1.3. Environmental, mechanical, and durability property assessment of concrete containing supplementary cementitious materials using life cycle assessment (Paper 3)

This study aims to conduct a life cycle assessment to evaluate the influence of mechanical and durability properties of concrete, transportation distance, and availability of SCMs on the GHG and CAC emissions from manufacturing concrete containing SCMs. The research question we are trying to answer is how the concrete mechanical and durability properties influence the GHG and CAC emissions from concrete containing SCMs.

Methods: This study will contain two sections: i) experimental analysis of mechanical and durability properties of concrete containing SCMs, and ii) LCA to evaluate the GHG and CAC emissions from concrete containing SCMs.

i) Experimental analysis of mechanical and durability properties of concrete containing SCMs
The experimental analysis will determine the effect of various SCMs on concrete's mechanical and durability properties. The experimental study will involve the following steps:

- A reference concrete mix containing 100% general use (GU) ordinary Portland cement (OPC) was designed, and fourteen samples were cast.
- Five different concrete mixtures as follows:

✓ 100% general use limestone (GUL) cement concrete
✓ 90% GU OPC + 10% pumice concrete
✓ 80% GU OPC + 20% pumice concrete
✓ 70% GU OPC + 30% pumice concrete
✓ 75% GUL + 25% fly ash

Were designed, and fourteen samples of each mix were cast.

- Compressive strength tests as per ASTM C39 were conducted on these samples at various design ages (3-day (d), 7-d, 28-d, 56-d, 90-d) to assess the influence of SCMs on the mechanical property of concrete.
- A rapid chloride ion penetration test (RCPT) as per ASTM C1202 was conducted on these samples to assess the influence of SCMs on the durability properties of concrete. The results of these experiments will be utilized in the LCA study to determine the effect of these properties on the GHG and CAC emissions from concrete containing SCMs.

ii) LCA to evaluate the GHG and CAC emissions from concrete containing SCMs
A Microsoft® Excel-based LCA will be developed to compare GHG and CAC emissions from a baseline scenario, i.e., concrete containing 100% general use OPC manufactured at a facility that uses fossil fuels as kiln fuel and concrete containing SCMs such as pumice and fly ash at different substitution rates. Generally, the functional unit used in LCAs on concrete manufacturing is taken as the volume of concrete ($1m^3$ of concrete). However, accounting for durability and mechanical properties of concrete impacts emissions associated with concrete production. Hence, this study's results will be presented for various functional units such as the volume of concrete, the compressive strength of concrete, and durability properties such as chloride ion penetration to assess their influence on the GHG and CAC emissions. Generally, SCMs are assumed to be unconstrained resources; however, due to the phase-out of coal plants, the availability of SCMs such as fly ash, slag, etc., has reduced. Hence, in this study, the availability of SCMs will be factored in the LCA along with the influence of transportation distances of SCMs on final emissions. This study will also discuss the implications of concrete containing pumice on its applicability in various structural components.

Results: (this project is 80% complete)

i) The results for the experimental analysis of mechanical and durability properties of concrete show that:

1. Higher substitution of pumice showed improved compressive strength even at early ages of concrete as compared to fly ash which is known to exhibit better strength at later ages of concrete
2. Mix 5 which is the general use limestone cement concrete and Mix 6 which is the 75% general use limestone cement concrete and 25% fly ash mixture, are yet to be tested for compressive strength at days 28, 56 and 90.

The results of durability test show that:

1. The increase in the pumice content in concrete mixes decreased the charge passed through the samples. Lower the charge passed indicates more durable the concrete mix against chloride ions, indicating better durability performance.
2. Mix 5 and 6 are yet to be tested for their durability.

ii) LCA to evaluate the GHG and CAC emissions from concrete containing SCMs
LCA model: This part of the study is still in progress.

1.4. Comparative life cycle assessment of greenhouse gas and criteria air contaminant emission reduction pathways in concrete manufacturing (Paper 4)

The objective of this study is to conduct a life cycle assessment to compare the GHG and CAC emissions from 100% general use ordinary Portland cement (OPC) concrete with concrete manufactured using four mitigation strategies: i) concrete containing cement manufactured using AFs as kiln fuel, ii) concrete containing SCMs, iii) concrete containing cement manufactured at a cement facility with CCS, iv) concrete manufactured using mineral carbonation curing. In this study we are trying to answer the following research question:

Which GHG and CAC emissions reduction strategy (AF use, SCMs in concrete, CCS, CCU) results in the highest emission reductions in the cement and concrete industry?

Methods: A Microsoft® Excel-based LCA model will be developed to compare five pathways: i) concrete containing 100% general use (GU) ordinary Portland cement (OPC) manufactured using fossil fuels as kiln fuel, ii) concrete containing 100% GU OP cement manufactured using AFs as kiln fuel, iii) concrete with supplementary cementitious materials (SCMs), iv) concrete containing 100% GU OP cement manufactured at a cement facility with carbon capture and storage (CCS) v) concrete manufactured using mineral carbonation (MC) curing. The GHG and CAC emissions from each pathway will be evaluated using an LCA framework and compared to discuss the potential trade-offs between these pathways.

i) Concrete containing 100% general use (GU) ordinary Portland cement (OPC) manufactured using fossil fuels as kiln fuel: The GHG and CAC emissions from the LCA conducted on concrete containing 100% GU ordinary Portland cement that is manufactured at a facility that uses fossil fuels as kiln fuels from paper 3 will be used in this section.
ii) Concrete containing 100% GU OPC manufactured using AFs as kiln fuel: This pathway's LCA will evaluate the GHG and CAC emissions from concrete that contains cement manufactured in a facility that utilizes AFs as kiln fuel. The LCA of cement is already conducted in paper 1 which will be utilized in this LCA.
iii) Concrete with supplementary cementitious materials (SCM): The LCA results for the supplementary cementitious materials scenario calculated in paper 3 will be utilized in this section.
iv) Concrete containing 100% GU OPC manufactured at a cement facility with carbon capture and storage (CCS): An LCA will be conducted to evaluate the GHG and CAC emissions from concrete containing GU OPC cement manufactured at a facility that uses AFs as kiln fuel coupled with CO_2 capture technology.
v) Concrete manufactured using mineral carbonation curing: An LCA will be conducted on concrete manufactured by replacing 100% cement with slag and curing it by injecting captured CO_2 while incorporating the effects on the resulting concrete strength and durability properties.

Comparing GHG and CAC emissions from the pathways mentioned above with conventional concrete will indicate which technology can provide the most considerable emission reduction benefits without compromising concrete strength and durability.

Results: **(this project is 60% complete)**

The results of LCA study on various pathways are summarized in Table 3.

Table 2. Results of LCA study on various pathways in concrete manufacturing.

Pathway	Pathway 1	Pathway 2	Pathway 3	Pathway 4	Pathway 5
Description	Cradle to gate LCA of 100% GU OPC concrete manufactured at a fossil fuel cement facility	Cradle to gate LCA 100% GU OPC concrete manufactured at an alternative fuel cement facility	Cradle to gate LCA 70% GU OPC+30% SCM concrete	Cradle to gate LCA 100% GU OPC concrete manufactured at an alternative fuel cement facility coupled with carbon capture storage (CCS) plant	Cradle to gate LCA 100% slag concrete cured with captured CO_2
% Completion	100%	100%	80%	10%	10%
Results	GHG and CAC emissions from 100% Natural gas use at cement facility calculated in chapter 1 LCA model will represent the environmental impacts from cement in this pathway. The emissions from other materials in concrete, such as aggregates, admixtures etc., will be utilized from chapter 3 LCA model.	GHG and CAC emissions from 100% alternative fuel use at cement facility calculated in chapter 1 LCA model will represent the environmental impacts from cement in this pathway. The emissions from other materials in concrete, such as aggregates, admixtures etc., will be utilized from chapter 3 LCA model.	GHG and CAC emissions from 30% replacement of 100% GU with pumice calculated in chapter 3 LCA model will represent his pathway.	Currently, a literature review has been completed for this pathway	Currently, a literature review has been completed for this pathway

2. Computational Fluid Dynamics, Laboratory Studies, and Combustion Guide, and Carbon Intensity Factor Calculations

The research in this area was mainly focused on preparation, delivery, and combustion of low carbon fuels, by developing specific combustion models that compare coal combustion (baseline) and various LCF in the kiln, as well as developing comprehensive apparatus and procedure for establishing low carbon fuel drying dynamics, a key missing link in running the fuel preparation operations. Below are a summary of the research activities and achievements:

2.1. Developing Combustion Numerical Models: The researchers at the Queen's University developed specific combustion numerical models that compare coal combustion and various low carbon fuel combustions in the kiln.

Methods: The extensive numerical modelling was focused on four aspects of combustion in the kiln: (1) developing and testing comprehensive physical and chemistry model of the coal combustion (baseline);

(2) developing advanced devolatilisation model for particle gasification inside the combustion chamber; (3) developing and implementing the NOx production model and (4) extending the two-phase aerodynamics of fuel particles from spherical particles to highly leaf-like geometries, characteristic of the flakes of shredded low carbon fuel. All the software work was based on the OpenFOAM (OpenCFD Ltd) software, while the geometry and meshing were done using the Salome platform.

Results: As the work on the baseline model setup progressed it became clear the weakest link in the physical/chemical picture was not in fluid dynamics, nor in chemistry, but in the devolatilisation process which was poorly modelled by the existing software modules. Rather than see this as a drawback, we saw an opportunity here to advance the state of the art in that direction. In the end, we developed numerical tools capable of modelling movement, evaporation, chemical reaction and heat transfer of individual fuel particles in the millions, obtaining realistic conditions recorded in the kiln operation using the conventional fuel. This outcome gives us confidence that the observed trends of change when conventional fuel (coal) is substituted by the low carbon alternative predicts the changes in process well. We did not have a chance to compare these alternative results with the experimental data since current kiln operation did not allow for such measurements to be made. Still, the results can readily be utilized in low carbon fuel trials. One of the variants that was examined involves separate low carbon fuel introduction from the kiln back wall (behind the burner, where the hot clinker falls into the clinker cooler chamber). All the modelling work was done using Reynolds Averaged (RANS) turbulence models and full Lagrangian particle tracking. Of the 5 different turbulence models tested, the k-ω-SST model proved to give best results. The devolatilisation method developed in this project is a dual-competing rate model, based on the constant rate and the single kinetic rate model combination. We did not have the capability to obtain our own combustion diagnostics of the particle devolatilisation but relied on the TGA sigmoidal curves obtained from the literature.

2.2. Developing comprehensive methodology for low carbon fuel preparation, focusing on material drying dynamics

Feed-stock moisture is critical parameter in handling the solid particulate fuel from the storage bin, through the shredder, transporting it to the kiln and introducing it into the combustion chamber through a modified solid fuel burner. There are three key differences between coal (or petcoke) and other kinds of low carbon fuels. While the term "low carbon" refers to its lower carbon footprint, since it has seen other uses, i.e. is recycled, or has been produced in a sustainable way, as a virgin biomass, for example. (1) the volume of the material to be introduced into the kiln is greatly increased due to its lower density and its lower caloric value per mass; (2) the particle size is much larger (several millimetres compared to fractions of a millimetre in case of coal or petcoke) and (3) the highly anisotropic shape, i.e. leaflike geometry, as opposed to more spherical shape of the coal powder. Each of these properties requires adjustments to the transport and the delivery system and at each level the moisture control is paramount.

How fast does the material need to be dried, what are the optimal airflow and temperature parameters, where is the best location for drying process? These are main questions arising in designing functional and safe delivery process. If the material is kept very dry in the storage it is prone to runaway heating, creating explosive mix, easy to ignite. However, if wet material is being transported into the kiln, it not only represents further reduction in its caloric value, but it makes fuel particles prone to conglomeration (caking), leading to frequent clogging of the delivery channels. This process is exacerbated by material heating due to friction and often high ambient temperature at the back of the kiln.

Methods: The research team at the Queen’s University developed a multilevel drying apparatus capable of effective testing of various materials in a meaningful volume (approx. 200 L), with simultaneous recording of temperature, pressure and moisture variations at 6 levels, with controlled dry air supply. A comprehensive series of experiments was conducted with this apparatus over a 6-months periods, usually running the facility full time 24 h/day.

Results:
Due to complexity of the material, it is not possible to predict their drying properties from the first principles. The intent here is to be able to test different materials on a routine basis. The data about optimal drying regime, specific to a particular material of interest can then be used to adjust actual drying regime of the material at hand and to develop optimal strategies of using waste heat from the kiln. Currently, more than 50% of the clinker cooling air heat is being wasted (the other 50% is being introduced into the kiln as preheated combustion air). Since the amount of available heated air after clinker cooling exceeds the air flow requirements for combustion in the kiln, this is an excellent opportunity to reduce heat waste.

3. System Level Scenario Models

3.1. Thermal Energy Flow model for alternative fuels co-fired with natural gas in the pre-calciner

Natural gas is available at a low price in Alberta and therefore it is used as the fuel of choice for clinker production by Lafarge Holcim plant (Exshaw, AB). To understand the impact of co-firing natural gas with AF on clinker production and thermal flow, the research team at the U of C developed a thermal energy flow (TEF) model for a 4,200 tonnes clinker per day cement plant to assess the performance of its clinker-making process using alternative low carbon fuel (LCF) to replace 50% (GJ basis) natural gas used in the clinker process (Nhuchhen et al., 2021, https://doi.org/10.1016/j.fuel.2021.120544).

Methods: The plant has a 4-stage cyclone preheater system followed by a long cylindrical vertical pre-calciner that completes the majority of the calcining reactions. The calcined raw materials move along with the flue gas from the pre-calciner through a bottom cyclone separator and then enter into the rotary kiln. The plant uses natural gas as a baseline fuel in the pre-calciner and rotary kiln. Three alternative fuels (High-density polythene (HDPE), railway ties 2 (RT2), and wood dust with 0%, 74%, and 100% biogenic carbon, respectively, were selected for use in the model. The results of the TEF model for the baseline case was validated using the plant specific data for the process temperatures, materials, and gases flow into and out of the kiln, pre-calciner and clinker cooler. The validated model was then used to predict the changes in the air, energy, and emissions intensities when AFs were co-fired to replace 50% GJ demand in the pre-calciner.

Results:

Here is a summary of the results:

1. Replacing natural gas by alternative fuels without increasing the oxygen concentration in the flue gas has little impact on thermal energy intensity and total air demand; however, to ensure complete combustion of solid fuels, this option may not be available to the plant operator.
2. Compared to textile, rubber requires less combustion air to burn, but requires more cooling air to cool down hot clinker from the kiln.
3. Replacing natural gas by AF and raising [O_2] concentration from 1% to 3% increases the average air demand by 21% and 13% respectively relative to the NG-based plant with 1% [O_2] in the flue gas (Figure 7).
4. Due to higher carbon intensity of AFs compared to the reference case fuel (NG), the total CO_2 emission intensity increases in the range of 1-8% and 4-14% when AFs are co-fired at 1% and 3% [O_2] in the flue gas respectively (Figure 7).
5. The use of carbon-neutral AFs such as wood dust at 3% [O_2] in the flue gas could avoid GHG emissions by up to 43 kg CO_2/t Clinker (5.8% reduction), equivalent to an emission reduction of 65,919 tCO_2 per year. Non-biogenic waste-derived fuels such as HDPE could increase GHGs by 5.5% (41 kgCO_2/ tClinker). The RT2 fuel with 74% biogenic carbon is projected to reduce GHGs by 1.6%.

Therefore, for AFs lacking biogenic carbon, the cement plant operator would face a trade-off between the cost of AFs and the cost of the excess CO_2 emissions with respect tot the emission benchmark.

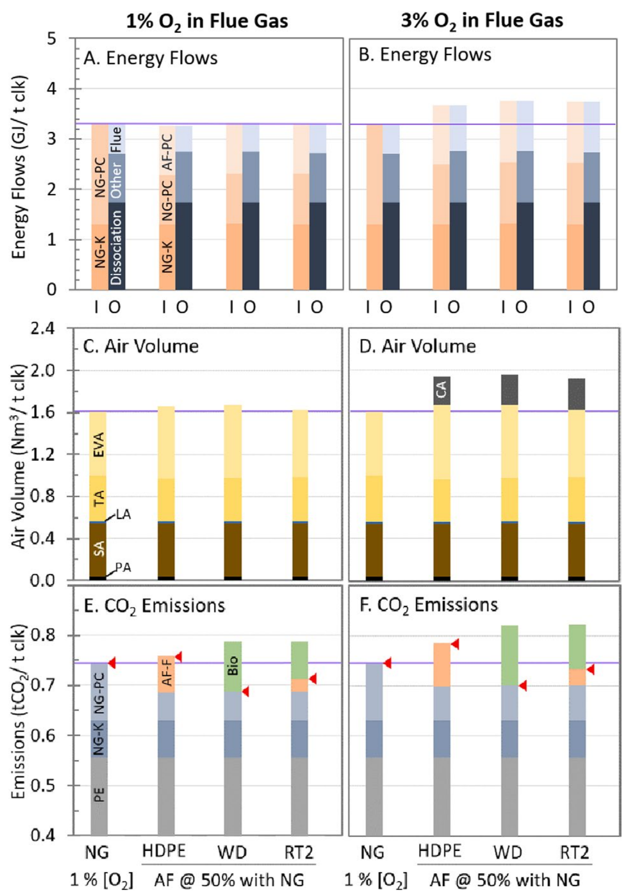

Figure 1: *Effects of AF on co-firing at 1% and 3% [O_2] in flue gas on energy flow, air demand and CO_2 emissions.*

3.2. Towards net-zero emission cement and power production using Molten Carbonate Fuel Cells

A study was performed on carbon capture and utilization for a natural gas-fired cement plant by the researchers at the U of C (Nhuchhen et al., 2022, https://doi.org/10.1016/j.apenergy.2021.118001). The study investigated the impact of an integrated low emission cement and power reduction system (LECAPP) on GHG emissions. Such system incorporates external reforming molten carbonate fuel cells to capture the CO_2 emissions from a natural gas-fired cement plant, by using natural gas or high-density polyethylene to generate the hydrogen demanded by the fuel cells while producing both low carbon electricity and a CO_2 stream for sequestration.

Methods: In this study, a process model of the LECAPP system (Figure 8) was developed in ASPEN Plus software to simulate the performance of molten carbonate fuel cells (MCFCs) in the capture of CO_2 emissions from the flue gas of an NG-fueled clinker production plant. Two scenarios were studied: 1) LECAPP with NG-based SG, in which a steam methane reformer was used to represent the syngas (SG) subsystem; 2) LECAPP with HDPE-based SG.

Results: The results showed that when CO_2 emissions are allocated to both clinker and electricity production, in scenario 1, the clinker accounts for 54.2% of the total CO_2 input to the LECAPP system. This means that the clinker is responsible only for 242 tCO_2/day of the total residual emissions. The remaining residual emissions are assigned to the net power (176 MW) produced by the LECAPP system, resulting in an electricity emission intensity of 48 kgCO_2/MWh. In the second scenario, calculated emission intensities for clinker and electricity production are 52 kgCO_2/ t clinker and 56 kgCO_2/MWh respectively. In both scenarios the emission intensities are less than 8% of that for the reference NG-fired clinker plant, and less than 17% of that for an NG-fired combined cycle power plant. For a cement plant producing 4,200 t of clinker, and a LECAPP system producing 174-176 MW of grid power, the total CO_2 avoided is estimated to be 4030-4048 tCO_2/day.

For a 4,200 t clinker-producing cement plant the LECAP system requires a geological capacity of 5,273 and 5,984 tCO_2/day for scenarios 1 and 2 respectively. This translates to 1.9-2.2 MtCO_2/yr or 76-88 Mt CO_2 over a 40 year life for the facility. Western Canada has the geological storage potential sites capable of managing this quantity of CO_2, which gives this region a significant advantage for clinker production.

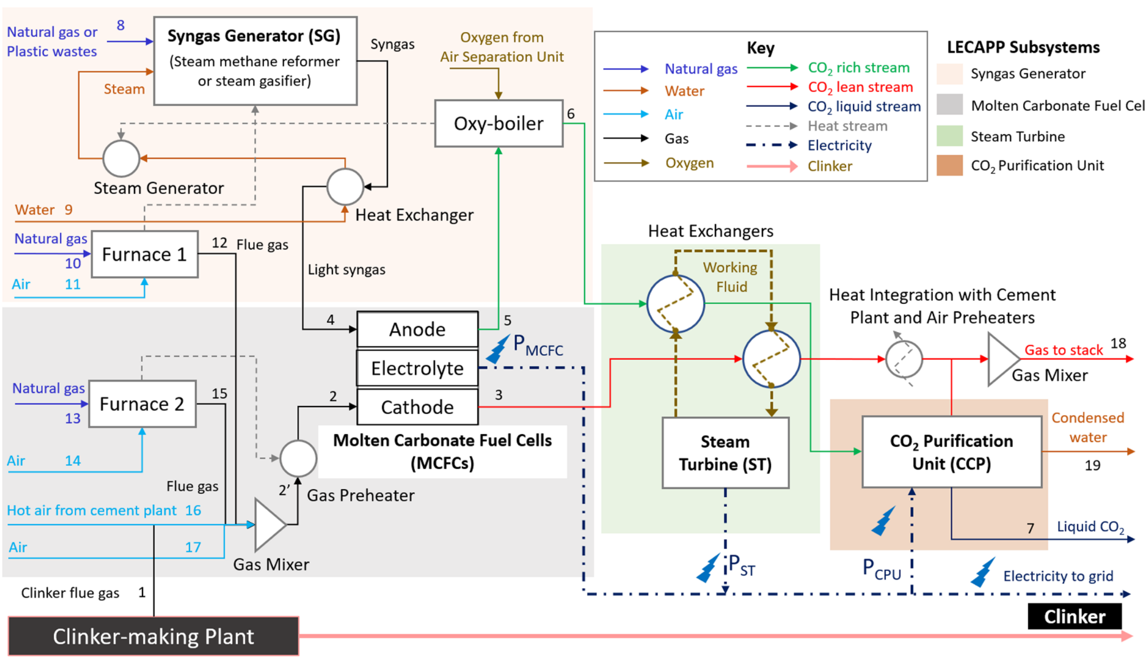

Figure 2: Schematic Process flow diagram of the LECAPP system incorporated with MCFC as an integrated CO2 capture and power cogeneration system.

3.3. Decarbonization of cement production in a hydrogen economy

To date carbon capture and storage (CCS) is the most promising technology for decarbonizing conventional cement making; however, the capture of the flue gas CO_2 and creating a concentrated CO_2 stream is challenging. One approach is to combust the fuel at near-pure oxygen (Oxy-combustion) rather than using air. This removes N_2 from the flue gas and makes the CO_2 content more concentrated. One way to produce near-pure oxygen is using an air separator unit (ASU), which is an energy intensive approach that results in indirect emissions associated with the electricity requirements of an ASU unit. An alternative source of pure oxygen could be the by-product of hydrogen production from water electrolysis. The researchers at the U of C performed a techno-economic assessment of oxy-combustion coupled to a CCS for a 4,200 tonnes clinker per day natural gas-fired cement plant. The source of oxygen was either from an ASU or from water electrolysis. The results showed that oxy-combustion increases both the thermal energy demand and electricity demand. The increase in electricity demand is less when electrolytic oxygen is used (67% increase). The levelized cost of oxygen supply for the pipelined electrolytic oxygen was \$35/tO_2 (200km) and \$13/tO_2 (20 km), which is less than \$49/tO_2 for an on-site ASU. The cost of clinker for the clinker plant without CCS increases linearly from \$84/t to \$193/t clinker at a carbon price of \$0/tCO_2 to \$150/tCO_2, respectively. With oxy-combustion and CCS, the clinker production cost ranges from \$119 to \$122/t clinker, reflecting a breakeven carbon price of \$39 to \$53/tCO_2. The lower cost of the electrolytic supply of the by-product oxygen compared to ASU oxygen must be balanced against the reliability of the supply, the pipeline transport distance and the charges that maybe added by the hydrogen producer.

4. Low Carbon Fuel Logistics Study

University of Calgary hired Tetra Tech to carry out a study on the logistics of Low Carbon Fuel use in Lafarge Exshaw plant in Exshaw, AB. The purpose of the study was to answer to the following questions:

1. What are the LCF sources and components including energy content, chemistry, and physical characteristics.
2. What are the costs, commitments and constrains associated with LCF extraction, pre-processing and shipment?
3. How might the supply chain be optimized including recommendations of suitable sites for processing and storage as well as inter-related issues around logistics, seasonality, competition and future possibilities for supply growth or decline.

The study was performed on eight selected LCF namely: Asphalt shingles, Carpet and textiles, Construction, renovation, and demolition (CRD) wastes, Non-recyclable rubber, Plastics, Tire fluff, Treated wood, and Wood products. Since Exshaw plant was the focal point for the ultimate utilization of these waste streams, the Calgary/Canmore/Banff corridor, as well as Edmonton area were used to define areas of interest for the study.

Tetra-Tech prepared a comprehensive report on each waste material, encompassing information such as estimated quantity, heating value, composition, co-processing data, material flow and supply chain, market data, logistic data, environmental permitting and regulations, value chain and greenhouse gas analysis. The complete report is shared with ERA.

The report provides valuable logistic information that can be used in the Lafarge decision making process in terms of selection of LCF for their Exshaw plant. The report confirmed Lafarge's data regarding the types of waste, volumes and various end used in the region. It helped Lafarge to target the specific AFs the plant would develop and to design the co-processing systems and business around these fuels.

This research is still ongoing. We will keep ERA updated on the status of the work and the published outcomes via email communications with our project advisor.

Commercialization

This section is not relevant for this project.

Lessons Learned

1. The biogenic CO_2 emissions are generally treated as carbon neutral by most regulatory frameworks. This requires the assumption that the biomass fuel sources will regrow and recapture the equivalent amount of carbon emitted during their combustion. However, this assumption ignores the regrowth and carbon uptake period, which will vary for different biomass species. Whether the CO_2 emissions result from fossil fuel combustion or biomass, and how the biogenic components of the AFs have been treated,

results in very different impacts. The calculation of GHG and CAC emissions and more precise accounting of biogenic CO_2 emissions in this study will help inform government policymakers.
2. Cement manufacturers are unaware of the prevention and mitigation measures concerning dust explosions. Therefore, before transitioning to AFs at cement kilns, the explosibility of dusts should be evaluated, and dust hazard analysis should be conducted at cement facilities.
3. The change in the compressive strength and durability of concrete when cement is replaced with SCMs influences the final GHG and CAC emissions associated with concrete mixes.

Environmental Benefits

The cement and concrete industries play an important role in Canada' infrastructure and green building ambitions. While the industry is a strong and innovative contributor to a growing clean economy, it is also a large emitter of carbon dioxide (CO_2). It is estimated that 5% of the world's carbon emission arises from the cement sector. In Canada the industry comprises 3.8% of the national total. In this project low carbon fuel pathways have been studied and the impact of different low caron fuels and scenarios on carbon emission intensities of this industry have been assessed or are under study.

In the Canadian cement industry over 90% of fuels used are coal, petcoke, natural gas, and other high fossil content fuels. Reaching a low carbon fuel of 30% co-fire is one of the objectives of the project. If this happens it will be a transformational change. When 30% replacement is achieved, this will result in a net GHG reduction of 8-10%, depending on the low carbon fuel characteristics.

Emission Reduction Impact

The results of this study show that replacing 50% of the energy content of natural gas by an alternative fuel mixture containing 50% construction and demolition waste, 20% railway ties, 14% asphalt shingles, 5% tire fluff, 1% carpet/textiles, and 10% plastics can result in up to 3.9% reduction in the GHG emissions depending on the GWP_{bio} value assigned to the alternative fuel and NOx emissions could reduce by 6.6%.

Replacing 50% of natural gas energy content with carbon-neutral AFs such as wood dust, and increasing [O_2] to 3% could avoid GHG emissions by 5.8%.

Using integrated low emission cement and power production technologies such as molten carbonate fuel cells to produce low carbon emission electricity as a by-product and a CO_2 stream for sequestration showed a 92% reduction in GHG emissions assigned to clinker production compared to a plant without carbon management.

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