UNIVERSITY OF CALGARY

"Carbon Utilization in Building Materials: A Study of Potentials for CO_2 Reductions in Canada"

by

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A RESEARCH PROJECT SUBMITTED

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE

DEGREE OF MASTER OF SCIENCE

GRADUATE PROGRAM IN SUSTAINABLE ENERGY DEVELOPMENT

CALGARY, ALBERTA

AUGUST, 2018

ABSTRACT

Greenhouse gas emissions from anthropogenic sources have been on the rise since the industrial revolution. Scientists now believe that these gases, specifically CO_2, is raising global temperatures and causing the climate to change. Reductions in CO_2 emissions need to be done to mitigate further negative impacts. Following the Paris Agreement in 2015 and the implementation of carbon pricing systems and penalties, reducing emissions has become a necessity. As renewable energy sources mature, other methods for reducing emissions need to be explored. The cement industry is a large emitter, with approximately 5% of anthropogenic emissions coming from process emissions. As a whole, the industry is motivated to reduce its carbon footprint. This study explores the potential for emissions reduction in Canada through the utilization of CO_2 is cement based materials and its economic feasibility.

ACKNOWLEDGEMENTS

I would like to thank Professor Ingelson for his guidance and support throughout the preparation of this project. In particular, with focusing the scope and encouragement. I would also like to thank Professor Herremans for her hard work and the time she dedicates to ensure the projects are of the highest quality. Lastly, I would like to thank my husband, Brendan Smith, for his patience, encouragement, helpful discussion and support, with which I would not have been able to complete the project.

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1.0 INTRODUCTION

Climate change has been a hot topic of discussion for more than three decades. My research is aimed at analysing a way to reduce carbon emissions in Canada, to help meet national climate targets through technologies which utilize carbon dioxide (CO_2) as a value-added product. Canada's national target is to reduce greenhouse gas (GHG) emissions to 517 $MtCO_2e$ from the approximately 738 $MtCO_2e$, or about 30% reductions (Government of Canada, 2018b). The current range and market for utilization technologies is already quite large and ever growing with government incentives to increase innovation in this field. Current, CO_2 is mainly used for enhanced fuel recovery and the food and beverage industry (Parsons Brinckerhoff, 2011). Additional uses are in plastics, fire suppressants, refrigerants, fertilizers and many more products. Through competitions such as the NRG COSIA carbon Xprize, Horizon 2020 and Emissions Reduction Alberta, innovation for carbon reduction and utilization technologies is expanding.

Concrete is the most widely used building material, it comprises 60% of the built environment and is the second most utilized substance after water (Jain, Deo, Sahu, & DeCrisofaro, 2014). Research has shown CO_2 is naturally adsorbed in cement products and can also utilize CO_2 through a process called carbonation, adding strength and durability. The cement industry, however, emits 5% of anthropogenic CO_2 emissions not including the emissions used as fuel. My research project investigates the potential and economic feasibility of CO_2 use in building materials, specifically cement, to reduce greenhouse gas emissions in Canada and help meet climate targets.

1.1 THREE DIMENSIONS

Three dimensions are used to investigate the research question; environment, economics and energy. Through these three aspects the objective is to understand the potential that the sequestration of CO_2 in cement materials has to reduce GHG emissions and help Canada meet its national climate target.

The environmental aspect is discussed both quantitatively and qualitatively. The objective is to understand the potential for CO_2 emission reductions, so the amount of CO_2 which can be sequestered in cement materials is analysed. Calculations are also done to get a better understanding of how much CO_2 can actually be reduced in Canada. Additionally, there is a broad discussion of other environmental impacts including life-cycle implications of the technology.

The cost of the carbon capture and storage process is presented in addition to the cost of actually sequestering CO_2 in cement materials. There is also a brief discussion of the CO_2 market in terms of supply and demand. Then cost estimates are determined for the entire process for one specific cement facility in Canada to identify the economic feasibility. Additionally, to better understand the current carbon story, a review of the carbon pricing systems across Canada is done with a discussion of the implications for the cement industry.

Lastly, carbon capture is a big variable for the entire process and it has the potential to reduce a significant amount of GHG emissions. A comparison between carbon capture at coal, natural gas and cement facilities are analysed with respect to other power generation sources. This analysis compares the levelised cost of adding carbon capture and storage (CCS) as well as the

cost of CO_2 avoided compared to other energy generation types to understand the overall feasibility of reducing emissions through carbon capture. Furthermore, energy use of CO_2 utilization in cement materials is also briefly discussed.

1.2 METHODOLOGY

The methodology used to investigate the research question from the perspective of the three dimensions described above is predominately through a literature review of both qualitative and quantitative aspects of CO_2 use in cement materials.

Research is first done into each aspect of the CCS process, types of technology available and the inherent cost of each part, i.e. capture, transport and storage. Next, an overview of the cement industry is done in terms of the overall manufacture process, and some of the top producers as well as global emissions and, in particular, emissions in Canada.

Mechanisms for CO_2 sequestrations from a chemistry perspective are examined and identification of how the technology can be applied, advantages and disadvantages of the process and examples of how it is being applied in the market place currently. One main driver for emission reduction is the emergence of carbon pricing systems. Types of systems and pricing are identified across Canada, with specific implications to the cement industry in Canada.

As part of the analysis, the CO_2 market is discussed in terms of supply and demand amounts, with estimates of future predictions. The cost of CCS at cement facilities is then compared with other energy sources as well as CCS from coal and natural gas facilities.

For the cost analysis, 5 scenarios are presented with calculations of CO_2 sequestration potential and cost estimates at a specific cement facility in Alberta. The scenarios include two types of carbon capture technologies compared with CO_2 utilization, geologic storage and CO_2 market sales. These estimates are then extrapolated to the rest of Canada to identify the potential of the technology. Lastly, implications from a life-cycle perspective are briefly analyzed as well.

2.0 BACKGROUND

2.1.1 GLOBAL WARMING AND CARBON DIOXIDE

The discussion about climate change started with the Rio Earth Summit in 1992, where the United Nations Framework on Climate Change (UNFCC) was adopted and set out a framework for actions to limit the average global temperature increases and associated climate change. The Rio conference made way for the Kyoto Protocol and then the Paris Agreement. The treaties have each updated the UNFCC, committed State Parties to reduce greenhouse gas emissions and come to a consensus that global warming is occurring and that anthropogenic CO_2 emissions are likely a main cause of it. Levels of reduction and signatories have changed over the years, but the current Paris Agreement has 195 signatories and deals with the GHG emissions mitigation, adaptation and financing starting in 2020 (UNFCCC, 2018). The goal is to keep global temperatures in this century from rising more than 2 degrees Celsius above pre-industrial levels and working towards a goal of less than 1.5 degrees Celsius (UNFCCC, 2018). Each country is responsible to set their own targets, plans and reports on their progress.

GHGs trap heat from the sun in the atmosphere causing a rise in average global temperatures. Some common GHGs are CO_2, methane, nitrogen oxides, sulfur oxides, and fluorinated gases. CO_2 is the greatest contributor of all the GHGs and most scientists believe is the main contributor to global warming (Woodford, 2017). CO_2 is a colorless, odorless incombustible and for some organisms, indispensable molecule. Consisting of a single carbon and two oxygens covalently bonded, this nonpolar molecule creates energy similar to infrared rays through the vibration of the oxygen atoms deforming and stretching around the carbon nucleus. This vibration energy adsorbs infrared rays resulting in the greenhouse effect. The incombustibility

of CO_2 makes it easily mixed with air and allows it to freely diffuse causing regional and global pollution.

With 35 billion tonnes of CO_2 emitted per year (Global CCS Institute, 2018b), a large part of CO_2 is generated by fossil fuels and industrial processes (EPA, 2017). Aside from switching to renewable energies and eliminating CO_2 production, which may take decades, reducing CO_2 emissions is one important way to stay on track in dealing with the climate change epidemic.

2.1.2 THE PAN-CANADIAN AND ALBERTAN INITIATIVE

In order to transition towards a low carbon future, the Canadian Government is investing $50 million dollars over 2 years to develop clean oil and gas technologies to help the hydrocarbon industry operate in more sustainable ways through the Energy Innovation Program (NRCAN, 2018a). One way this money is being used is by investing $10 million into the Alberta Carbon Conversion Technology Centre (NRCAN, 2018b). This facility is jointly funded by Alberta Economic Development and Trade and NRCAN, with a combined total of $20 million (InnoTech Alberta, 2017). It will be located in Calgary at the new Shepard Energy Centre, where carbon utilization technologies can be tested on an near-commercial scale. The first to use the centre are the finalists of the NRG COSIA Carbon XPRIZE which will be awarded in 2020 (InnoTech Alberta, 2017).

3.0 CARBON CAPTURE, SEQUESTRATION AND UTILIZATION

3.1 CARBON CAPTURE METHODS

Carbon capture and storage is a major technology to reduce CO_2 emissions. The capture of CO_2 is generally accomplished in one of 4 ways; Pre- or post-combustion, oxyfuel combustion, or directly from the air (Global CCS Institute, 2018a). The most common is post-combustion capture, where CO_2 at the end point of a combustion unit from the flue gas emitted from any pressurised combustion (Koytsoumpa et al., 2017). The CO_2 is separated primarily by using techniques such as adsorption, phase separation and membranes (Global CCS Institute, 2018a). For pre-combustion capture, the input carbon-based fuel is first broken down to hydrogen and carbon monoxide creating a synthetic gas or syngas either via oxidation or gasification. For example, for natural gas through the process of reforming and gasification, carbon monoxide and water are converted to hydrogen and CO_2 via a water gas shift reaction. The CO_2 can then be removed with solvents, adsorbents or membranes (Koytsoumpa et al., 2017).

The oxyfuel combustion capture method entails removing nitrogen from the air through a cryogenic air separation unit or via membranes. The removal of nitrogen leaves almost pure oxygen, which is combusted resulting in mainly CO_2 and water in the flue gas (NRCAN, 2016). Lastly, CO_2 can be captured directly from atmospheric air using adsorption methods however at very low quantities (Koytsoumpa et al., 2017). This technique has been used in oxygen separation plants, space crafts and submarines (Koytsoumpa et al., 2017).

3.2 CARBON TRANSPORT

The captured carbon is then either stored on site or if the option is available, however more likely, needs to be transported under pressure to the storage location. Like other fuel gases,

pipelines are the most common way to transport large quantities of CO_2 (CCS Association, 2018). Ships are another alternative method used on a smaller scale in Europe mainly to transport food quality CO_2 (CCS Association, 2018). Trucks and rail can also be used, however, generally only for very small scale operations and short distances.

3.3 CARBON STORAGE

In terms of the storage of the CO_2, there are 37 current large-scale projects globally either in operation, construction or development with a storage capacity of 37 million tonnes per year (Global CCS Institute, 2018b). These are divided into two types of facilities, either dedicated geological storage or enhanced oil recovery, which is sometimes considered a utilization technology rather than storage. Of these 37, there are 4 dedicated geological storage facilities operating globally, 2 in Norway, 1 in Canada and 1 in the US, as well as 1 under construction in Australia and 8 more in development, in Australia, Norway, China, South Korea, and the UK (Global CCS Institute, 2018b). Large-scale facilities are at a scale of at least 400,000 tonnes of CO_2 annually and at least 800,000 tonnes for coal plants (Global CCS Institute, 2018b). The Quest facility is the only dedicated geological storage facility in Canada. The Great Plains Synfuel Plant and Weyburn-Midale and Boundary Dam Carbon Capture and Storage facilities are the two-operational enhanced oil recovery facilities in Canada with 2 more in construction and set to be completed in 2018 (Global CCS Institute, 2018b).

3.4 CARBON UTILIZATION

Although CCS is one way to reduce CO_2 emissions, it is not feasible for all CO_2 emitters due to geographical constraints and high cost of transportation. Carbon utilization technologies have been emerging steadily over the past several years and has been viewed as one of the most

promising ways to combat climate change. However, it does face some challenges. Capturing CO_2 is an expensive process and is currently only feasible on carbon-intensive processes, which means it excludes CO_2 from transportation, agriculture and housing (Planete Energies, 2017). The carbon footprint needs to be considered on the entire life-cycle compared with conventional alternatives, especially if the carbon is to be stored in the product through disposal. And, as with storage, the transportation cost restricts manufacture locations.

Carbon is being used in a range of products and processes currently. As mentioned above, enhanced oil recovery, which can be considered both utilization or storage, is a highly-used process. Other usages in the chemical and oil sector are urea production, polymer processing, reservoir stimulation and fracing (Koytsoumpa et al., 2017). The food industry also uses CO_2 in carbonation of beverages, coffee decaffeination, wine production and baking soda (Koytsoumpa et al., 2017). Other areas where CO_2 usage can be found are in heat pumps, algae cultivation, pharmaceuticals, pH reduction in the pulp and paper industry, and cement (Koytsoumpa et al., 2017).

The purity of CO_2 varies among usages. Naturally, food and beverage usages require higher purity with 99.9%, while industrial or medical uses require 99.5% (Pringle, 2015). The main difference between the purity is the amount and type of impurities allowable in the CO_2. Impurities such as ammonia, benzene or other hydrocarbons are less of an issue for industrial uses as compared with the food and beverage industry (Pringle, 2015).

Overall, the carbon utilization industry is estimated to have a potential for using 3.7 billion tonnes of CO_2 per year (10% of the total global emissions) which equates to roughly US $0.8-1.1 trillion (Koytsoumpa et al., 2017).

3.5 COST OF CCS

Capture

Reducing CO_2 emissions through carbon capture increases the cost of traditional methods of electricity generation or industrial process. The main impacts on the cost are the capital expenditures associated with CO_2 capture and compression, increased fuel and energy required, and operations and maintenance costs associated with the process. The largest impact is due to the increased energy requirements and capital cost of the capture facility.

The levelised cost of electricity, sometimes called the life-cycle cost, is a measure used to the describe the generating cost of power generation technology (Parsons Brinckerhoff, 2011). It is calculated as the present value of costs per unit of energy generated over the lifetime of the plant (Irlam, 2015). The plant costs include capital costs, fuel cost and efficiency, run time or capacity factor, operations and maintenance as well as rate of return paid to owners and financers (Irlam, 2015). The added levelised cost of including CCS to a facility is up to 40% for gas-fired power plants and up to 60% for coal plants (Parsons Brinckerhoff, 2011) or US $82-93/MWh for gas fired plants or US $115-160/MWh (Irlam, 2015). These values are lower than offshore wind, solar PV and Solar thermal, and comparable to hydropower, geothermal, onshore wind, nuclear and biomass (Irlam, 2015). This is due to capacity factors versus capital

costs of each technology. This capture cost is similar, if not higher for other industrial processes such as cement or steel manufacture (Irlam, 2015).

The cost of CCS increases the cost of production, however, generally a different metric is used to describe cost-effectiveness of a technology. The cost of CO_2 avoided, or abatement cost is used to assess the cost of a technology's ability to avoid or reduce emissions (Parsons Brinckerhoff, 2011). In other words, the cost of CO_2 avoided describes the cost of reducing emissions compared with the amount of fossil fuels used. This describes the cost of reducing emissions while producing the same amount of product and is expressed by \$/tCO_2 not emitted. The calculation is not simple since a facility which captures CO_2, also generates additional CO_2 due to the lowered efficiency from the power required to capture the CO_2. In other words, although, emissions are reduced, the total reduction in emissions is less than the emissions reduced since additional CO_2 is emitted from the increased energy used for capturing the CO_2. The calculation is done by taking the difference in levelised cost with and without CCS relative to the decrease in emission of a reference point.

This metric allows technologies to be better compared in terms of their cost-effectiveness of reducing emissions. In terms of CO_2 avoided, CCS is a competitive technology when compared with other sources of electricity such as traditional power plants or renewables. With a cost of about US \$48-109/tonne for coal fired plants and US \$74-114/tonne these values are comparable to biomass, higher than hydropower, geothermal onshore wind and nuclear, but less than offshore wind, solar PV and solar thermal (Irlam, 2015).

Transport

The cost of transporting CO_2 can be quite variable mainly due to the distance and mode of transport. In terms of pipeline transport, it has been estimated that the annual cost of CO_2 transport for each 100km of pipeline is US \$1.50/tCO_2 and US \$2/tCO_2 (Anderson, 2017).

Storage

In terms of storage costs, estimates generally do not include the cost of active pressure management, post-closure monitoring, long-term stewardship and liability in terms of risk of mitigation and remediation, and costs of public outreach and increasing acceptance for storage projects (Anderson, 2017). The cost of CO_2 storage is generally combined with transport cost and very dynamic. It depends on volumetric capacity and the number of reservoirs available in a region (Anderson, 2017). The cost will also change as low-cost reservoirs will be filled first and higher-cost reservoirs will fill up later (Anderson, 2017). Costs are estimated at US \$5/tCO_2 to US \$100/tCO_2 (Anderson, 2017).

In Canada, Shell's Quest project, which is located near Edmonton, has taken 1.3 Mt of CO_2 in the first 13 months of operations (Bakx, 2017). The project in total cost CAD \$1.3 billion, with CAD \$745 million for the Alberta government and CAD \$120 million from Ottawa (Bakx, 2017). This project has not yet produced a profit, but it does reduce the amount of carbon tax the company has the pay. Without government funding, it is estimated that the project would require a carbon tax of CAD \$100/tonne to cover the capital costs and operation costs (Bakx, 2017).

4.0 THE CEMENT INDUSTRY

4.1 BACKGROUND ON CEMENT – CONCRETE FACTS

There are three main anthropogenic sources of CO_2 emissions, oxidation of fossil fuels, land-use changes and deforestation, and carbonate decomposition, of which cement is the largest source (Andrew, 2018). Cement is a binding material which has been used since ancient times, but production worldwide accelerated rapidly after World War II. Currently, global production levels equal about half a tonne per person per year (Andrew, 2018) or about 4.8 billion tons in 2017 (Market Publishers, 2018). Production of cement has quadrupled since 1990, primarily due to rapid economic development in China (Andrew, 2018). China is the worlds top cement producer, with 2,400 million metric tons produced in 2017, which is over half the world's cement, followed by India with 280 and the US 86.3 (Statista, 2018a). In Canada, cement is produced in Ontario, Quebec, British Columbia and Alberta, with a little in Nova Scotia with a combined production capacity of 18.58 Mt (Table 1). In 2016, production was 11.9 Mt, where 3.6 Mt was exported, primarily to the US, and the remaining 8.3 Mt was used within Canada (Edwards, 2017).

The manufacturing of cement is an energy intensive process, and is uneconomical to transport long distances. This means that many countries are producing it themselves and not much is being traded on the global market. With rising urbanization and industrialization and growing population, there is a huge demand for shelter and infrastructure which is increasing the global cement demand.

Cement is a hydraulic binding material, composed of silicates and oxides, that when exposed to water, set and harden. The most commonly used cement is Ordinary Portland cement. It is primarily used in stucco in wet climates, applied as mortar near sea water and is a main component in concrete (Statista, 2018a). Concrete is the most widely used building material due to its strength and durability. This material is used in nearly all construction projects including homes, buildings, roads, and bridges. It is a popular choice because it has a long service life as well as its high thermal mass and low air infiltration which insulates homes and buildings making them more energy efficient (NRMCA, 2012). The residential sector accounts for the greatest market, at 59%, primarily attributed to the rise in urbanization (Technavio, 2016). Another advantage is the potential for adding industrial by products such as fly ash and slag to concrete which helps reduce the carbon footprint and the waste quality in landfills (NRMCA, 2012).

Cement has been widely used throughout history. In the ancient world, Egyptians used calcined gypsum, and the Greeks and Romans made mortar by heating limestone to make lime and made concrete by adding coarse stones (WHD Microanalysis Consultants Ltd., 2018). By adding crushed volcanic ash or clay and crushed slag, it was discovered that the cement would set underwater, and could be used to build harbours and lighthouses. In 1845, the first modern day Portland cement was creating using a mixture of chalk and clay, which was fired at a temperature of 1400-1500C (WHD Microanalysis Consultants Ltd., 2018). This produces clinker and other minerals which are very reactive and cementitious (WHD Microanalysis Consultants Ltd., 2018).

4.2 CEMENT PRODUCTION

Calcium, silica, aluminum and iron, when combined together are the ingredients in Portland cement (Cemex, 2017). The manufacturing process requires careful control to produce cement which conforms to specific chemical and physical specifications. Manufacturing plants are usually located near quarries, where raw materials are mined. Raw materials consist of limestone, chalk, shells, shale, clay, sand or iron ore (Cemex, 2017). The raw materials are reduced in size by 2 crushers, first to five inches in size, then pulverized to ¾ inch (Cemex, 2017). The raw materials are then proportioned at the manufacturing plant to create cement with specific composition.

Two methods of manufacture can be used, dry or wet. The dry method consists of grounding the raw material, blending it and drying it in a kiln (Cemex, 2017). The wet method is more complex. First, raw materials are proportioned, water is added to create a slurry then ground and blended (Cemex, 2017). The slurry is fed into a tilted, rotating cylindrical kiln and heated to 1430-1650C. Cement clinkers, grey-black pellet, form at 1480C from several chemical reactions (Cemex, 2017). Once the clinkers have cooled, they are mixed with gypsum and ground to a fine powder, creating Portland cement.

4.3 CO_2 EMISSIONS FROM CEMENT PRODUCTION

Two areas of cement production result in CO_2 emissions, process and energy emissions. Process emissions are from the chemical reaction resulting in cement clinkers, where carbonates are decomposed into oxides and CO_2 through the addition of heat (Andrew, 2018). The chemical formula is generally, $CaCO_3 + O_2 \rightarrow CaO + CO_2$. This process has been estimated to produce 5% of anthropogenic CO_2 (Andrew, 2018). The other source of emissions is from the burning of

fossil fuels to raise temperatures in the kiln to well over 1000°C which requires significant energy. Energy emissions adding about 60% on top of the process emissions, resulting in about 8% of global CO_2 emissions from cement production (Andrew, 2018).

Generally, process emissions are the only emissions included in calculations of emissions from cement production, where energy emissions are accounted for in fossil fuel emissions (Gibbs, Soyka, & Conneely, 2001). Process emissions are estimated by multiplying the amount of clinker produced by the clinker emission factor (Gibbs et al., 2001). The clinker emission factor is estimated either by using the Intergovernmental Panel on Climate Change (IPCC) fraction of lime in clinker default value or by calculating the average lime concentration in the clinker (Gibbs et al., 2001).

The cement industry is the second largest emitter of CO_2 from industrial process, with electric power generation in the top spot (ERA, 2018a). The top producer of cement, China is also the top emitter with almost 800 $MtCO_2$ in 2014 (Andrew, 2018).The emissions from China's cement industry are more than all the emissions in Canada. The next closest emitter is India, at almost 150 $MtCO_2$, followed by the US, Turkey and Vietnam which all emit under 50 $MtCO_2$ (Andrew, 2018).

4.3.1 CO_2 EMISSIONS FROM CEMENT PRODUCTION IN CANADA

In Canada, there are 16 cement manufacturing facilities, located in British Columbia, Alberta, Ontario, Quebec and Nova Scotia (Table 1). The oldest facilities date back to 1904 and 1906. Total combined production capacity from these facilities is 18.58 Mt, however actual cement

production totals are only about 11.9Mt. Of that, 3.6Mt are exported, primarily to the US. The remaining 8.3Mt are used within Canada (Edwards, 2017).

Cement production is classified to be the heavy industry sector, that accounts for between 7%-14% of total GHG emissions (Environment and Climate Change Canada, 2017). In 2016, this was 10,211,227 tonnes CO_2e, with the majority of emissions from CO_2, namely 10,185,658 tonnes CO_2e, and the rest from CH4 and N2O (Table 1). This amount equates to almost 0.86 tCO_2/ tonne of cement produced. The majority of the emissions are in Ontario, with 53% followed by Quebec, BC and Alberta (Figure 1).

In 2007, the global cement industry came together and decided to reduce emissions from 2Gt to 1.55 Gt by 2050 (Monkman, MacDonald, & Hooton, 2016). The goal is despite the fact that cement production is expected to rise by 50% (Monkman et al., 2016). The industry is looking for ways to be more efficient through alternative fuels, higher efficiency equipment, CCS, and innovative approaches. With changing government policies and global motions towards carbon pricing system, there will be big changes coming to the industry. These changes can be seen at several facilities across Canada, such as the recent modernization to more efficient equipment and the addition of an EcoDome at the Exshaw Cement plant in Alberta (Lafarge, 2017), CO_2 capture for process validation of a photobioreactor at St. Marys Cement in Ontario, and CO_2 capture for electrochemical reduction technology at the Richmond facility in BC (IEAGHG, 2013).

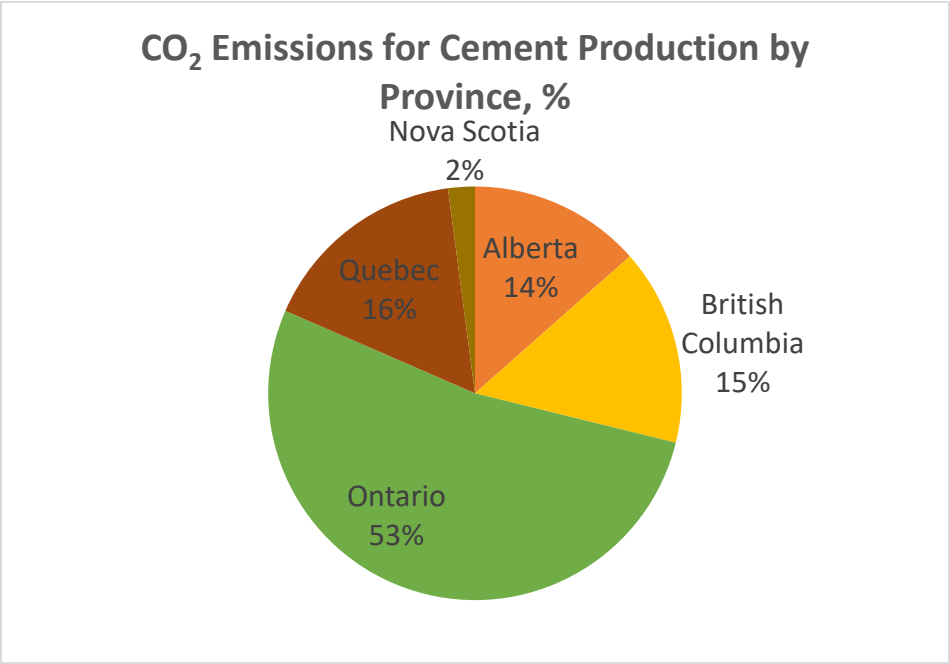
Table 1 . List of all cement facilities in Canada including the estimated production amount and greenhouse gas emissions.

Company	Facility Name	City	Province	Year	Production Capacity	Estimated Production*	CO_2	CH_4	N_2O	Total
					Million Tonnes	Tonnes	Greenhouse Gas (tCO_2e)			
Ciment Quebec Inc	Cimenterie de Saint-Basile	Saint-Basile	Quebec	1951	1.57	817827.73	700009.6	65.16	831.5094	700906.3
Essroc (Italcementi Group)	Picton Plant	Picton	Ontario	1958	0.79	754699.5585	645975.8	1270.275	639.806	647885.9
Lafagre Canada Ltd	Brookfield Cement Plant	Brookfield	Nova Scotia	1965	0.61	231861.4966	198459	36.75	119.2	198615
Lafagre Canada Ltd	Cimenterie de Saint-Constant	Saint-Constant	Quebec	1967	0.99	637248.5513	545445.1	146.395	584.1694	546175.6
Lafagre Canada Ltd	Bath Cement Plant	Bath	Ontario	1973	1.1	920739.8908	788096	1120.225	1837.17	791053.4
Federal White Cement Ltd	Woodstock Plant	Woodstock	Ontario	1979	0.47	420628.7898	360032	101.075	427.928	360561
Lafagre Canada Ltd	Exshaw Cement Plant	Exshaw	Alberta	1906	1.33	899455.2539	769877.7	1395.108	1168.279	772441.1
Lafagre Canada Ltd	Kamloops Plant	Kamloops	British Columbia	1970	0.22	131338.2619	112417.4	40.4	166.284	112624.1
Lafagre Canada Ltd	Richmond Cement Plant	Richmond	British Columbia	1957	1.31	804573.4946	688664.8	567.49	960.3944	690192.7
Lehigh Hanson Canada	Edmonton Plant	Edmonton	Alberta	--	1.38	594229.0735	508623.1	75.2675	701.5814	509399.9
Lehigh Hanson Canada	Delta Plant	Delta	British Columbia	1904	1.1	766746.56	656287.3	1017.068	1574.006	658878.4
Holcim (Canada) Inc.	Usine de Joliette	Joliette	Quebec	1965	1.47	968323.9606	828825	199.75	1099.62	830124.4
Holcim (Canada) Inc.	Mississauga Cement Plant	Mississauga	Ontario	1956	2.21	1187955.595	1016816	6184.533	705.9918	1023707
St. Marys Cement Inc	Bowmanville Cement Plant	Bowmanville	Ontario	1968	2.94	1916088.89	1640053	284.0075	1367.105	1641704
St. Marys Cement Inc	St. Marys Cement Plant	St. Marys	Ontario	1912	0.82	638659.4272	546652.7	131.3625	382.5724	547166.6
Colacem Canada Inc	Cimenterie Kilmar	Grenville-sur-la-Rouge	Quebec	--	0.27	209623.4661	179424.6	144.4375	223.9172	179793
					18.58	**11900000**	**10185659**	**12779.3**	**12789.53**	**10211228**

* Actual production calculated using C02/tonne value

(Government of Canada, 2016) (Edwards, 2017) (Industry About, 2016)

Figure 1. Graph demonstrating CO_2 emissions from cement production by province.



(Government of Canada, 2016)

5.0 USING CO_2 IN CEMENT PRODUCTION

5.1 MECHANISMS OF CO_2 UPTAKE IN CEMENT

Cement-based materials such as raw cement, hardened cement paste, mortar, concrete and cement waste have the ability to adsorb CO_2 (Jang, Kim, & Lee, 2016). CO_2 utilization in cement-based materials is completed though a process called carbonation. Carbonation in cement chemistry is defined as a chemical reaction between cement hydrates and CO_2 (Jang et al., 2016), which is also classified as a type of mineral carbonation.

The concept of cement carbonation is not new, however, in the past was viewed as a negative factor as with time it deteriorates the hydration products. This is called weathering carbonation. The main binders in cement is calcium-silicate-hydrate, which when exposed to atmospheric CO_2 decalcifies, meaning it eventually becomes a silica gel and loses its binding properties and in turn its durability (Zhang, Ghouleh, & Shao, 2017). Additionally, the elevated alkalinity of the cement product increases the vulnerability of the steel reinforcement, causing it to corrode. However, in recent years, studies have shown that there are positive effects from carbonation of cement hydrates specifically in early-age carbonation.

The basic principle or mechanism is to fix the CO_2 in the form of thermodynamically stable carbonates through the carbonation reaction (Jang et al., 2016). The most common carbonation reaction in hardened cement paste and concrete, is through the reaction with calcium hydroxide or calcium silicate hydroxides, which constitute about 60% of the volume in Portland cement (Zhang et al., 2017). Calcium hydroxide or calcium silicate hydroxide is found in solid state in cement paste and is highly water soluble (Jang et al., 2016). The basic reaction is where calcium (silicate) hydroxide in solid state reacts with CO_2 gas forming calcium carbonate and

water. For this reaction to occur, there much be a specific amount of moisture in the system, this is discussed in section 5.3. In practice, this process is a bit more complicated.

For calcium hydroxide, the reaction occurs in capillary pores within the hardened cement paste (Jang et al., 2016). These pores are filled with a solution with high pH levels, consisting of cation such as sodium and potassium and hydroxide ions. As the CO_2 gas is injected into the system, it dissolves into the pore solution and forms carbonic acid. The carbonic acid then reacts with the sodium and potassium, forming highly water soluble and thus reversible compounds. However, the carbonic acid also reacts with the calcium hydroxide which dissolves in the pore solution, forming calcium carbonates precipitate, which has low solubility and thus low reversibility. Because this reaction is irreversible, the concentration of calcium ions decreases. As this continues, calcium hydroxide concentrations decrease, and more calcium carbonate is produced, which lowers the pH levels in the cement-paste (Jang et al., 2016).

The process is very similar for calcium silicates and has been shown to occur after a degree of calcium hydroxide has been consumed (Jang et al., 2016). The reaction is with CO_2 in aqueous conditions and creates calcium silicate hydrate ($xCaO\ SiO_2\ yH_2O$ or C-S-H) and calcium carbonate (Zhang et al., 2017). However, this can result in decalcification of C-S-H with excessive carbonation resulting in silica gel, SiO_2, and calcium carbonate (Zhang et al., 2017). Decalcification influences the structural integrity and strength of the cement product. With adequate moisture and sufficient time, hours to days, the result is increased mechanical strength.

Other carbonation reactions which may occur are with calcium sulfoaluminate hydrate, cement clinker minerals, magnesium-derived hydrates and supplementary cementitious material. These are not discussed further in this study, and more information can be found in Jang et al. (2016) and Zhang et al. (2017).

5.2 HOW IT WORKS

As mentioned earlier, there are two ways concrete can sequester CO_2, through weathering and early-age carbonation. Estimates have shown up to 32 million tonnes of CO_2 emissions can be reduced through early-age carbonation in North America (Wagner & Hagel, 2014). The main products where early-age carbonation is used is in curing concrete blocks, pavers and segmented retaining walls. Weathering carbonation is most common in Portland cement concretes and mortars due to their porous nature, allowing for easy CO_2 diffusion. Although weathering carbonation is seen as a negative factor, sometimes for this reason cement structures are seen as passively green since they sequester small amounts of CO_2 over time (Wagner & Hagel, 2014).

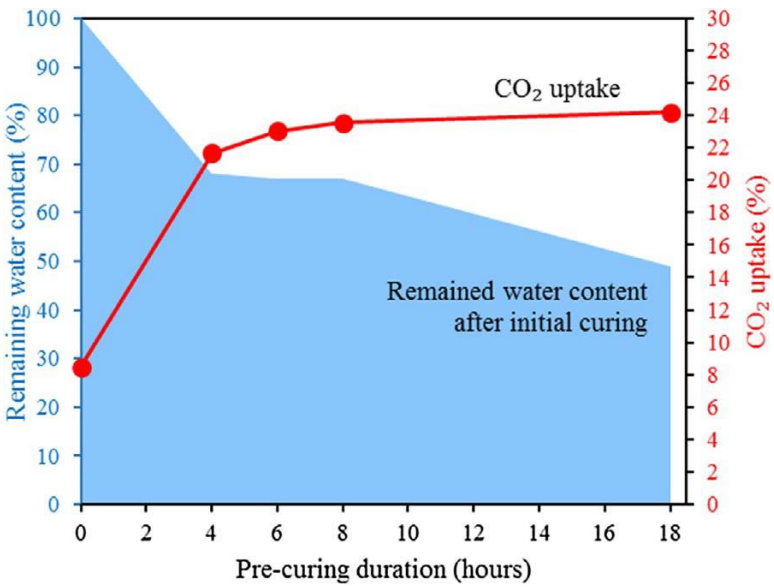
Early-age carbonation can take place at either the concrete mixing stage or as part of the curing phase. During the mixing stage, gaseous CO_2 is injected into the mixer where the reactions occur. The curing method is a more controlled method, where CO_2 is fed into a curing chamber which is under low or high-pressure steam. Curing cement with CO_2 has been seen to decrease the curing duration (Jang et al., 2016). This method has 4 steps.

The first step in the process is the pre-curing process. This step controls the moisture content in preparation for carbonation and is especially important for effective carbonation. Because most

of the reactions occur in aqueous state, the right amount of moisture is critical. At this stage, ambient temperatures are about 20-25°C and relative humidity is about 40-60% (Zhang et al., 2017). Once the concrete form is cast and demolded, water is either removed, if there is excessive moisture, or water can be added. Generally, once the cast is demolded, the water to solid ratio is 0.4, and reduces as carbonation occurs. Early water loss promotes high CO_2 uptake, which slowly plateaus after about 40% water loss (Figure 2) (Zhang et al., 2017).

The next step is exposure to CO_2. This can happen in one of two ways, enclosed (pressurized vessel) or flow-able (open chamber). The enclosed method has higher reaction efficiency, while the flow-able method is less energy intensive (Zhang et al., 2017). In most cases, this process has been done at room temperature, however elevating the temperature can increase CO_2 diffusion but will also reduce aqueous solubility (Zhang, Ghouleh, & Shao, 2017). The last phase is post-curing, where after carbonation, the system is rehydrated. The rehydration assured hydraulic reactions occur and has shown to increase the strength and pore structure (Zhang et al., 2017).

Figure 2. Graphical representation of CO_2 uptake and water content changes over time



(Zhang et al., 2017).

Carbonation mixing is another method to sequester CO_2 through early-age carbonation. With carbonation mixing technology, this increases the amount of potential sequestration capacity from only pre-cast concretes to cast-in-place concretes too (Zhen, Zhen, & Shao, 2017). Studies have shown that although carbonation mixing can increase CO_2 uptake, it can also decrease the strength gain because the cement particles develop a carbonate coating which affects the cohesion between particles (Zhen et al., 2017). If carbonation mixing is followed by air mixing, this problem can be minimized. Combining carbonation mixing and carbonation curing, CO_2 uptake can increase by up to 30% (Zhen et al., 2017).

5.3 FACTORS AFFECTING CARBONATION

There are many factors which affect the carbonation process. One factor is the partial pressure of CO_2, which influences the diffusivity of CO_2 in the medium. Carbonation at low pressure will

progressively carbonate and porosity will decrease as calcium carbonate precipitate is produced, lowering the ability of CO_2 to diffuse in the medium (Jang et al., 2016). However, with high pressure carbonation, large quantities of CO_2 enter the medium and diffuse through the medium before the pores are closed, enhancing the carbonation process (Jang et al., 2016).

Temperature affects the rate of carbonation. As temperature rises at atmospheric pressure, gas diffusivity increases and so does the amount of calcium ions which leach into the pore solution (Jang et al., 2016). However, the amount of CO_2 which is dissolved in the pore solution decreases (Jang et al., 2016). The source of CO_2 can also affect the carbonation process where, highly concentrated CO_2 gas is generally used, increasing the carbonation rate (Jang et al., 2016).

The water content is an important factor affecting the diffusivity and reactivity. Water in the pore spaces is a huge factor required in the leaching of calcium, while low water content will inhibit the ionization of CO_2 and dissolution of calcium hydroxide (Jang et al., 2016). The diffusion of CO_2 is much higher in the atmosphere then in water, so high water content does not allow for CO_2 diffusion. Ideal relative humidity is 50-70% (Jang et al., 2016).

Additionally, the chemical composition, particle size and surface area all play a role. Smaller particle sizes increase the surface area which in turn increases the rate of carbonation. As well as more reactive chemicals will also increase the rate. Similarly, porosity and permeability of the medium directly affects the diffusivity of CO_2. High porosity is therefore favorable. The physical and chemical properties of the raw materials, as well as the compaction and curing

conditions all affect the porosity of the cement-based material. Heavy metals such as lead, cadmium and nickel decalcify C-S-H which also increases the porosity (Jang et al., 2016).

5.4 CO_2 UPTAKE

CO_2 uptake or sequestration can be estimated theoretically and experimentally. Theoretical calculations estimate a maximum CO_2 uptake for carbonation curing between 0.32-0.5 tCO_2/ton material (Jang et al., 2016). Experimentally, CO_2 uptake is commonly estimated though the mass gain method, comparing the mass before and after carbonation. The other method which is commonly used examines the decomposition behaviour of carbonates. Experimental results have shown an uptake for carbonation curing ranging between 0.07-0.24 tCO_2/ton material (Jang et al., 2016). Uptake values vary based on mineral composition, temperature, pressure, humidity and time. The maximum amount of CO_2 uptake is calculated theoretically based on the stoichiometric mass balance. Carbonation mixing on its own has a CO_2 uptake of about 0.034 tCO_2/ton material, while when combined with carbonation curing this can go to 0.108 tCO_2/ton material (Jang et al., 2016).

The efficiency of carbonation is calculated as the percentage of experimental uptake over theoretically calculated CO_2 uptake or as the degree of carbonation as the percentage of CO_2 uptake over the maximum capacity of CO_2 uptake determined theoretically (Zhang et al., 2017). The efficiency is a measure of the amount of original material compared to the efficiency of consumption (Jang et al., 2016). The efficiency, in general, was found to slightly vary, but on average 30% efficiency is found through various studies. When carbonation proceeded for more than 4 hours, the efficiency went up as high as 50%.

5.5 EFFECTS OF CO_2 CARBONATION ON CEMENT PRODUCTS

As discussed above, the main benefit of CO_2 sequestration in cement materials is the potential for increased strength gain and durability due to the denser microstructure. This method has the potential for lowering the carbon footprint of the cement industry by 36% (Jang et al., 2016). Carbonation is a form of permanent CO_2 sequestration and required no additional chemical additives or pre-treatment. Energy consumption is also relatively low since the process generally occurs at room temperature and does not require any pressure changes (Jang et al., 2016). Furthermore, the addition of fly ash to the concrete can further add to the strength gain and lead to additional reduction in emissions.

Studies have also been done comparing steam curing with carbonation curing (Zhang et al., 2017). The low permeability of concrete after carbonation curing has the added benefit compared with steam curing of resisting freeze-thaw conditions, since the permeability and reduced pore size does not allow for water saturation and restricts ice formation (Zhang et al., 2017). Furthermore, the low permeability and higher alkalinity, allows carbonation cured concrete to inhibit reactions with sulfate, acids and alkali silica and acts as a protective measure lowering the aging process (Zhang et al., 2017). Carbonation cured concrete not only reduces the carbon footprint, but with increased strength, less concrete is needed and the resistance to environmental factors can lead to increased life of the concrete product. Additionally, this technology qualifies for credits towards Leadership in Energy and Environmental Design (LEED) certification for buildings (Wagner & Hagel, 2014).

Given these benefits, the main concern about carbonation cured concrete is the effect on steel reinforcements such as rebar. The high alkalinity and presence of chloride ions can destroy the

protective coating on steel reinforcements leading to corrosion (Zhang et al., 2017). However, the low permeability may be an advantage since it hinders diffusion within the concrete. The full effects of corrosion are not well known yet (Zhang et al., 2017). The other main challenge is that although carbonation mixing can occur, the CO_2 uptake is lower and the strength gain is decreased, so carbonation curing is the most effective method. However, carbonation curing is restricted to pre-cast products, limiting the potential uses to products such as masonry units, paving stones, cement boards and fiber boards (Ashraf, 2016).

Comparing pre-cast and cast-in-place concrete, there are many attributes to consider. Preparation and installation for pre-cast concrete is generally simpler and less time consuming than cast-in-place projects, with projects taking a matter of hours compared with several days (Advance Concrete Products Co, 2018). An additional benefit of pre-cast concrete is that it is not sensitive to weather conditions, where as cast-in-place concrete projects are delayed by rain, snow or sleet, and set much slower in colder temperatures (Advance Concrete Products Co, 2018). However, cast-in-place concrete is completely customizable, although this means that last-minute changes are difficult and costly. With the benefit of using less material and labour for installation, pre-cast concrete also costs less, about half or a third of the price (Firszt, 2014). Including carbonation to the process for pre-cast projects does increase the cost, but cost may still be competitive with cast-in-place projects.

5.6 COST OF CO_2 CARBONATION

To discuss the feasibility of CO_2 sequestration through cement carbonation, economic effectiveness also needs to be examined. The cost to sequester one tonne of CO_2 is indicated by the product of the power consumed, hours of operation and the rate of power per kW, divided

by amount of cement-based material (1 tonne is used here) and the efficiency of sequestration (Jang et al., 2016). In the US this is calculated to be between US \$11-37/tCO_2, which is based on a rate of power of US \$0.079/kW, power consumed at 11kW/h and efficiency ranging from 7-24% (Jang et al., 2016).

An additional cost can be attributed as ancillary income. Ancillary income is due to the higher strength properties meaning less cement is required. This equates to a cost of US \$1-6 /tCO_2 (Jang et al., 2016). Adding this cost, the total cost of sequestration through carbonation curing is estimated between US \$12-43 /tCO_2. Additional cost of capture and transport also need to be included.

Applying this cost to the production of 1 cement block (or CMU, concrete masonry unit) is show in Table 2. Using a range of capture or bulk cost between US \$20-40/tCO_2 (Jang et al., 2016), this is discussed further in section 7.1. The transport cost is highly variable, a is excluded here, however this cost is commonly included in the cost of capture. Multiplying the total cost by 7% or 24% uptake in a cement block, the additional cost of carbonation curing of one cement block varies between US \$0.004/block and US \$0.036/block.

Table 2. Cost of carbonation curing for one cement block.

Item	Low Cost	High Cost	Units
Capture	$20	$40	/tCO_2
Carbonation	$12	$43	/tCO_2
Total Cost	$32	$83	/tCO_2
7% Uptake per block	0.126	0.126	kg CO_2
	$0.004	**$0.0105**	$/block
24% Uptake per block	0.432	0.432	kg CO_2
	$0.0138	**$0.0359**	$/block

(Shao, 2014)

5.7 CO_2 CARBONATION IN PRACTICE

The cement industry is motivated to reduce emissions. Energy efficiencies are already being implemented to reduce GHG emissions by using alternative fuels, energy efficient processes and equipment and supplementary cementitious materials, however innovative technologies are needed to help meet their national climate targets. Through various emission competitions, some companies are already using the carbonation curing technology.

Solidia Technologies

One of these companies is called Solidia Technologies (Solidia). A development between Rutgers, the University of New Jersey and Solidia researchers, the company has created a new form of concrete, Solidia Concrete, which can reduce emissions by about 70% (ERA, 2018a). Solidia was a funded by Emissions Reduction Alberta, receiving $500,000 for research & development for the technology. The company does not only use CO_2 in the curing phase, but it has also developed a concrete which uses Solidia Cement, which has a low-lime composition (Jain, Deo, Sahu, & DeCrisofaro, 2014). The use of low-lime raw materials has the advantage that it is produced at lower temperatures than Portland cement (Jain et al., 2014). An additional

advantage is that Solidia Cement does not react with water in the curing phase, but does require moisture for the reaction to occur (Jain et al., 2014). The lack of reaction with water means the water can be reused and reduces water consumption. Application of Solidia Concrete are paving stones, concrete blocks, railway ties, roof tiles, pervious concrete (concrete with large pores allowing for rapid water drainage, used sometimes for concrete walkways), and wet-cast paving stones (Jain et al., 2014).

CarbonCure Technologies

A company based out of Nova-Scotia and a finalist in the NRG COSIA Carbon XPRIZE Challenge, CarbonCure Technologies (CarbonCure) has teamed up 5 companies to create an end-to-end value chain (Smith, 2018). Starting with carbon capture by Sustainable Energy Solutions using a cryogenic CO_2 technology from a cement plant near Calera, Alabama, transportation using Praxair, Inc. and Glenwood concrete operation in Atlanta, enabling the use of CarbonCure technology (Smith, 2018). The products are then used in construction projects in Atlanta. The CarbonCure technology is used in both ready mix concrete and concrete masonry products by injecting a precise amount of CO_2 into the central mixer (CarbonCure, 2018). Some of the projects the technology has been applied to is the MGM National Harbour in Washington DC, a retail office building in Atlanta, and York University Bergeron Centre in Toronto (CarbonCure, 2018).

McGill University

A research group at McGill University has also received funding from ERA for research and development of cement carbonation. The group lead by Dr. Yixin Shao, builds on the

carbonation process to use COS to produce artificial aggregates which is carbonated with CO_2 in addition to carbonation curing (ERA, 2018b). The group has also developed a method to produce low-cost CO_2 through a self-concentration absorption process (ERA, 2018b).

Many companies are innovating and developing technologies around carbonation curing. The development of alternates to cement can play a role in reducing emissions in itself, not requiring such high volumes of cement manufacture. This can also help the inherent problem with steel reinforcements increasing the potential usages of carbonation cured cement products.

6.0 CARBON PRICING SYSTEM

Following the adoption of the Paris Agreement in 2015, and the Vancouver Declaration on Clean Growth and Climate Change Declaration in 2016, four Canadian Provinces have adopted a carbon pricing system (Good, 2018). A working group, called the Working Group on Carbon Pricing Mechanism, was established to provide options for the design of carbon pricing systems to meet Canada's emission reduction targets. With the adoption of the Pan-Canadian Framework on Clean Growth and Climate Change, the government outlined the principles agreed upon in the Vancouver Declaration and the Working Group on Carbon Pricing Mechanisms. The framework includes a timeline on incorporating a carbon pricing system, a scope of coverage, promises revenues remain within each jurisdiction, includes a five-year review in 2022 and reporting requirements as well as incorporates a federal backstop (Good, 2018).

In January 2018, the federal government of Canada released a legislative proposal for the *Greenhouse Gas Pollution Pricing Act*. The Act is for a national carbon pricing system, that would require provinces and territories to implement a carbon price by January 2019. If a province or territory does not adopt their own carbon pricing system or do not meet federal standards, they will have the federal government system, or backstop, imposed on them. The pricing scheme within the Greenhouse Gas Pollution Pricing Act starts at CAD $10 per tCO_2e, rising by CAD $10 each year up to CAD $50 per tCO_2e in 2022 (Good, 2018).

There are two types of carbon pricing systems, direct pricing and cap-and-trade, both types are in Canadian provinces. The direct pricing system is employed in British Columbia and Alberta. The direct system is implemented through a carbon levy or tax and provides a transparent and

explicit price on emissions. The output-based pricing system (OBPS) is a type of direct pricing system also employed in the two provinces and is used to reduce emissions from large GHG emitters while exempting them from paying for fossil fuel consumption (Government of Canada, 2018a). Instead GHG emission limits are calculated based on annual economic production and facility compliance credits are issued up to the annual GHG emission limit. If a facility emits more than the specified limit, they must buy additional compliance credits from facilities with a surplus, by getting verified offset credits, or buying them from the government.

British Columbia has had a carbon tax system since 2008 and is currently at CAD \$35/tCO_2e, rising by CAD \$5 each year (Good, 2018). The OBPS was introduced in BC in 2016 and currently only applies to LNG facilities. In Alberta, the carbon levy was introduced in January 2017, and is currently at CAD \$30/tCO_2e (Good, 2018). In 2018, Alberta introduced this for large final emitters, or LFEs, which emit more than 100,000 tCO_2e, through the *Carbon Competitiveness Incentive Regulation,* discussed further below. Large facilities must acquire verified emission offsets, apply emission performance credits and pay CAD \$30/tCO_2e for exceeding the limit (Good, 2018).

The cap-and-trade system is currently used in Ontario and Quebec for facilities emitting more that 25,000 tCO_2e per year. The system sets a limit on GHG emissions within the economy, and there is a pool of emission allowance credits (1 allowance = 1 tCO_2e) given out by the government (Ontario, 2018). Some credits are given out at no charge and the remaining credits are sold at auction, purchased from other emitters or acquired as verified emission credits. The emission cap is lowered over time and prices on allowance credits rise. Ontario and Quebec are now integrated with California as part of the Western Climate Initiative and in February 2018

held their first joint auction (Good, 2018), with the current auction price at CAD \$18.56/tCO_2e (US \$14.53/tCO_2) (WCI, Inc, 2018) . Currently, Ontario's cap is set at 142.3MtCO_2e (Ontario, 2018) and 82.1MtCO_2e in Quebec (ICAP, 2018). However, after recent elections, Onatrio's government has announced it will eliminate the cap and trade system (McCarthy, 2018).

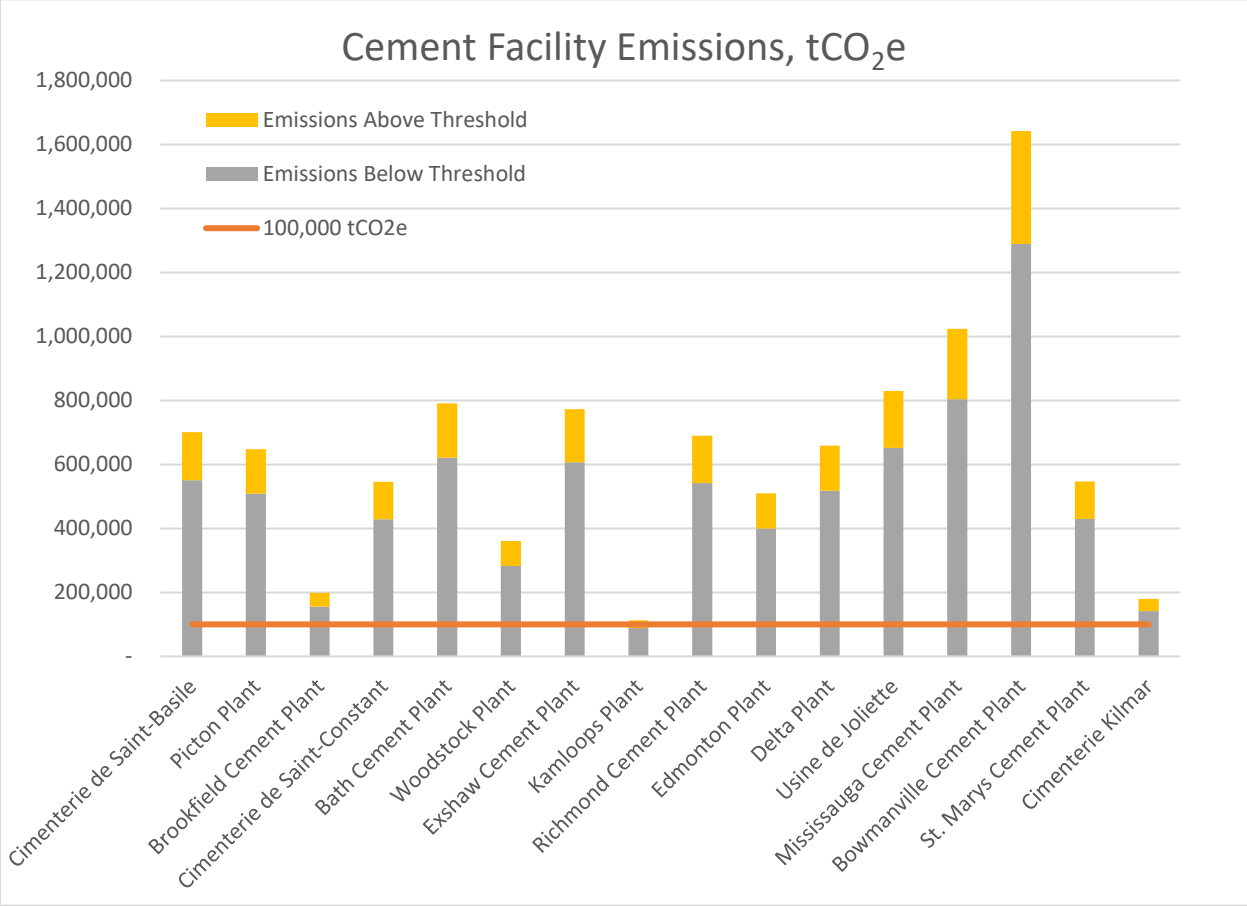
The Nova Scotia government does not yet have a carbon price system, but it has passed amendments to the *Environment Act* in October of 2017 to introduce a cap-and-trade system in the province. The plan is to impose the system on facilities emitting more than 100 ktCO_2e per year (Good, 2018). Unlike the Ontario and Quebec system, the plan is to have most of the allowances be distributed at no charge and there is no plan to join other jurisdictions cap-and-trade system.

Carbon Competitiveness Incentive Regulation

The *Carbon Competitiveness Incentive Regulation* in Alberta has replaced the *Specified Gas Emitters Regulation* which applies to Large Final Emitters (LFEs) emitting more 100,000 tCO_2e or more in 2003 or any subsequent year or an eligible facility which has opted in (Government of Alberta, 2018). The regulation outlines the benchmarking methodology as recommended by the Climate Change Advisory Panel. For all cases aside from electricity, oil sands and mining, the benchmark is set at 80% of production-weighted average emissions intensity (Government of Alberta, 2018). This is the case unless the benchmark is more stringent than the best performing facility, than the benchmark is set to the "best-in class benchmark". Industrial processes, including cement facilities, have a benchmark set at 100% of sector average.

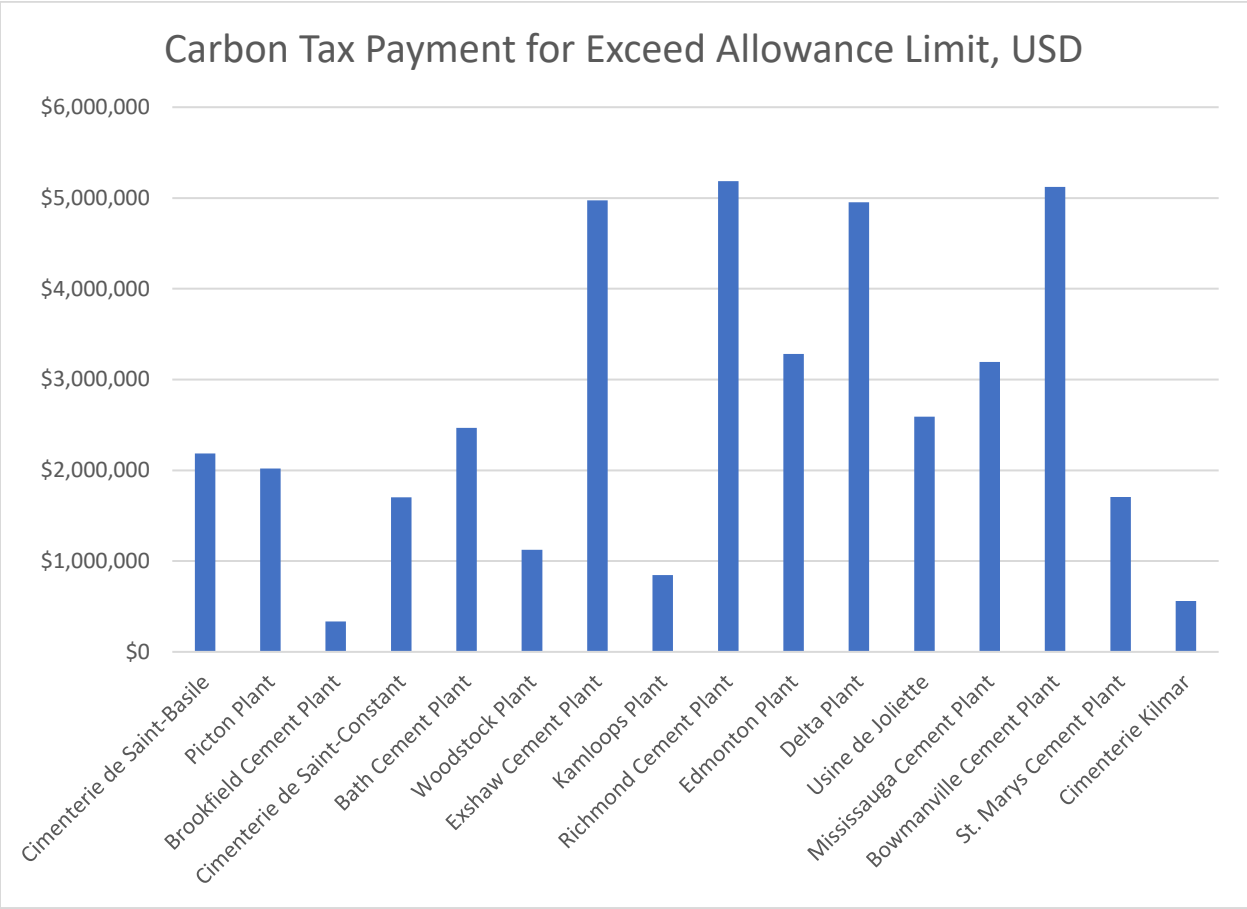
Based on the regulation in Alberta, the actual benchmark for cement is 0.7853 tCO_2/tonne cement in 2018, and will be 0.7763 tCO_2/tonne cement by 2022 (Carbon Competitiveness Incentive Regulation, 255/2017). Figure 3 illustrates the total emissions for each cement facility across Canada as well as showing the amount of emissions which are above this benchmark or threshold. These values are based on Alberta regulation threshold, which is not accurate for each Province, but demonstrates a general target of almost 10% of CO_2 reductions for cement facilities. Respective carbon prices are illustrated in Figure 4. This graph assumes the Alberta threshold and minimum carbon pricing relative to each province, as discussed above. For Nova Scotia, which does not currently have a carbon price, using the Federal Backstop of CAD \$10/tCO_2. Additionally, Figure 4 does not take into account any potential carbon credits each facility may already have.

Figure 3. Graph of emissions from each cement facility across Canada including emissions above the threshold



(Government of Canada, 2016) (Carbon Competitiveness Incentive Regulation, 255/2017)

Figure 4. Carbon tax payment based on respective provincial carbon price by facility



(Good, 2018)

7.0 ANALYSIS AND DISCUSSION

7.1 MARKET EVALUATION AND ECONOMICS

Understanding the CO_2 market is essential when considering CO_2 reuse and its potential for accelerating GHG reductions. As of 2011, the CO_2 demand was estimated at 80 Mtpa, with 50 Mtpa of that used in EOR and the rest primarily in the food and beverage industry (Parsons Brinckerhoff, 2011). Estimates of current technology growth and increased implementation and commercialization of prospective technologies predict a demand of 140 Mtpa by 2020 (Parsons Brinckerhoff, 2011). Examples of demand estimates for future potential technologies are shown in Table 3. Concrete curing is shown to have a demand between 30-300 Mtpa, meaning its potential for future use is estimated to be quite high.

Table 3. Potential future demand of new technologies

Emerging uses	**Future potential non-captive CO_2 demand (Mtpa)**
Enhanced coal bed methane recovery (ECBM)	30 <demand <300
Enhanced geothermal systems – CO_2 as a heat exchange fluid	5< demand <30
Power generation – CO_2 as a power cycle working fluid	<1
Polymer processing	5< demand <30
Chemical synthesis (excludes polymers and liquid fuels/ hydrocarbons)	1< demand <5
Algae cultivation	>300
Mineralisation	
Calcium carbonate and magnesium carbonate	>300
Baking soda (sodium bicarbonate)	<1
CO_2 concrete curing	30< demand <300
Bauxite residue treatment (‘red mud’)	5 < demand < 30
Liquid Fuels	
Renewable methanol	>300
Formic acid	>300
Genetically engineered micro-organisms for direct fuel secretion	>300
CO_2 injection to conventional methanol synthesis	1< demand <5

(Parsons Brinckerhoff, 2011)

Comparing the demand with the supply which is about 500 Mtpa for high-concentration sources and 18000 Mtpa for dilute sources such as power, steel and cement plants (Parsons Brinckerhoff, 2011), means there is a huge supply surplus. With the surplus likely growing globally, market prices are also likely to continue to drop. Additionally, restriction on CO_2 emissions may also add to the supply surplus.

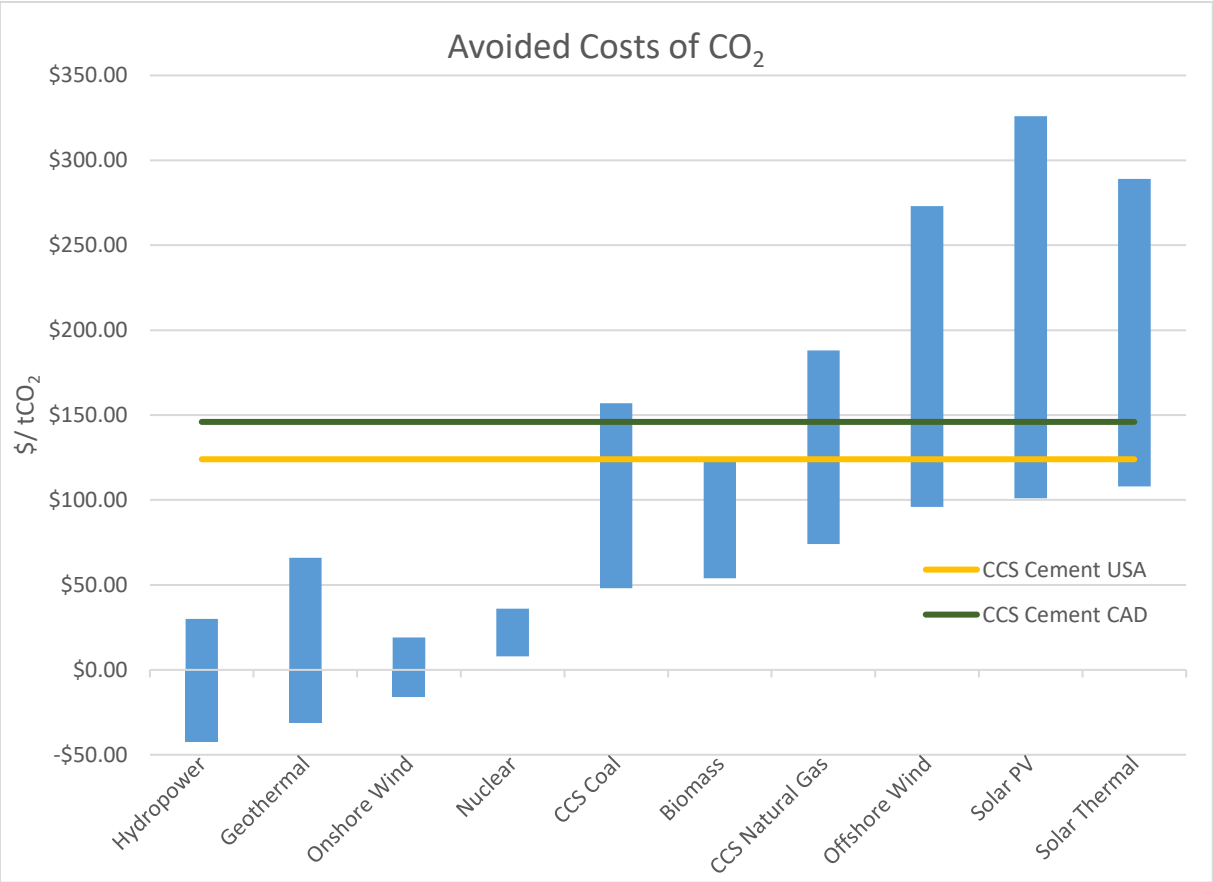
The supply of CO_2 primarily comes from natural geologic reservoirs or when the gas is produced as a by-product from industrial process. Bulk CO_2, which is unprocessed CO_2, with about 95% CO_2 content, is sold on the market and distributed through dedicated pipelines (Parsons Brinckerhoff, 2011). Generally, bulk CO_2 is sold privately, meaning that the price is also negotiated privately and not available to the public. However, prices have been seen anywhere between US$3 to US$ 40/tCO_2 (Parsons Brinckerhoff, 2011). With supply increasing, this is expected to be the upper limit for future purchase prices.

With a high percentage, 80% in the case of EOR (Parsons Brinckerhoff, 2011), of CO_2 currently supplied from natural sources, this presents an opportunity to replace natural CO_2 with anthropogenic CO_2. The cost of capture is a driving force to allow this to happen. Some sources, such as high concentration sources like ammonia plants, ethanol production and natural gas processing, have low cost of capture, while dilute sources are more expensive.

Cement manufacture emits a dilute source of CO_2 and thus has a higher cost to capture. Often, as described earlier, levelized cost is not the best for comparison, so cost of CO_2 avoided is used. For a cement facility, the levelized cost without CCS is US$101/tonne and the cost with

CCS increases by 68% to $170/tonne (Irlam, 2017). This means that the cost of CO_2 avoided for a cement facility is US$ 124/tonne. However, the cost ranges by country from US $104/tonne to US$194/tonne, where in Canada the cost is US $146/tonne. This range is mainly due to changes in labour cost, which is higher in Canada (Irlam, 2017). Figure 5 show the comparison of cost avoided between different power generation sources and is compared to CCS from cement as well as natural gas and coal facilities. This comparison was also discussed in section 3.5.

Figure 5. Graph of Avoided Cost of CO_2 comparing power generation technologies with CCS from cement



(Irlam, 2015)

7.2 COST ANALYSIS

Under the Paris Agreement, Canada is committed to reduce GHGs to 517 Mt by 2030, or 30% below 2005 levels, which were 738 Mt (Government of Canada, 2018b). As discussed earlier, emissions from the cement industry in Canada account for 10,211,227.67 Mt CO_2e, from which 10,185,658.83 Mt are from CO_2 emissions. If feasible, the ideal scenario for carbon utilization would be to capture CO_2 directly from the cement facility and inject it into the product on-site. This case would limit the cost of CO_2 transport, maximize the carbon offset, and have the largest reduction in the carbon footprint. To evaluate the feasibility of doing this, a cost analysis is provided for one cement facility, Exshaw Cement Plant in Alberta. A summary of the analysis inputs is shown in Table 4, that includes production and emission details for the Exshaw Cement Facility. Five scenarios are considered for comparison (Table 5) and are discussed below.

Scenario 1 is as a base case. In this scenario, two types of carbon capture are considered; oxyfuel combustion or post-combustion technology. These technologies vary quite a lot in terms of capital investment cost, US $379.32 M and US $647.28 M respectively (IEAGHG, 2008). In addition to capital cost, annual operations cost which include fuel, power, fixed and variable operations and capital charges, add up to US $94.656 M for oxyfuel combustion and US $150.104 M for post-combustion (IEAGHG, 2008). For comparison, annual operating cost for a cement facility without carbon capture is US $76.1 M (IEAGHG, 2008). These types of capture technologies have a capture potential between 77-95% (IEAGHG, 2008), for simplicity, an average of 83% is used in this analysis. For scenario 1, the assumption is that 100% of the CO_2 captured at the facility is sold to the market at the bulk price and 100% of the produced cement

is sold business as usual, without CO_2 utilization, at a cost of US $113/tonne of cement (Statistica, 2018b). Since the bulk price is estimated between US $20-$40/tCO_2 (Jang et al., 2016), an averaged value of US $30/t$CO_2$ is used here. This equates to a total revenue from CO_2 and cement sales of approximately US $120 M. With this scenario, sufficient revenue is generated to cover only the annual operating cost for oxy-combustion capture. However, the limitation with this case is that it is assumed there is a market for all the CO_2 captured.

Scenario 2 and 3 are similar to scenario 1, both assuming on-site carbon capture using either of the two technologies, as described in scenario 1. Scenario 2 considers carbon utilization with 7% CO_2 uptake, which equals to about 63000 tCO_2 sequestered. The remaining CO_2 is assumed to be sold to the market at the bulk price. Assuming all cement produced is used to sequester CO_2, including the cost of utilization, which is averaged at US $27.50/t$CO_2$, the total revenue for scenario 2 is about US $83 M. Similarly, in scenario 3 the high end of CO_2 uptake at 24% is considered. With the same assumptions as scenario 2, the total revenue is about US $79 M. The lower revenue in scenario 3 is due to the higher amount of CO_2 sequestration resulting in less CO_2 for bulk sale. One limitation with these two scenarios is the lack of price per tonne difference between products with 7% and 24% uptake. An estimated price of US $93/tonne is used (Canadian Building Materials, 2018), however this price is for precast cement products without CO_2 sequestration. With increased strength and potential to use less cement, this price would realistically vary between 0%, 7% and 24% CO_2 uptake. The increase in strength adds value to the product, which should increase the price, however the increased strength also results in less cement needed, potentially bringing down the price. Without an exact pricelist, the price without CO_2 is used as an estimate.

For scenario 4, the assumption that CO_2 is captured at the cement facility remains the same, but geologic storage is considered instead of utilization. It is assumed that all the captured CO_2 is sequestered in a geologic reservoir. With on-site capture and utilization, the cost of transport was not considered, however for geologic storage the transport of CO_2 needs to be accounted for. An estimate of US \$5/tCO_2 is used, which assumes a transport distance of about 200-300 km (Jang et al., 2016), resulting in about US \$3M for CO_2 transport. An average cost for geologic storage of US \$ 52.5/tCO_2, leads to a cost of about US \$33.5 M for CO_2 storage. There would generally also need to be an additional cost for leakage mitigation, but this cost is unknown. With no value added or potential for revenue generation, the total cost of geologic storage is at a loss of almost US \$37 M, not including the cost of capture. Geologic storage has a potential to store large amounts of CO_2, economically, without subsidies the cost is very high and carbon prices are still too low to make this financially feasible.

The last scenario assumes CO_2 is purchased at the bulk price and not captured on-site like in the other scenarios. In this case, although the cost to purchase CO_2 is about US \$22 M, including the cost of transport, there is a lower revenue compared with scenario 2 and 3. The lower revenue is due to the lack of profits from the sale of the remaining CO_2. However, this case does not need to generate sufficient revenue to compensate for the capital and operation cost of carbon capture. The same amount of CO_2 is sequestered, however the biggest limitation with this scenario is that it does not reduce the CO_2 emissions from the cement industry directly. Therefore, this scenario has potential to offset emissions resulting in carbon credits, but at 7% uptake, this is not enough to fully offset the CO_2 emissions below the threshold and carbon levy still needs to be paid, at about US \$2.4 M.

With no value added, potential for adverse environmental effects and high cost, geologic storage is not the ideal scenario. Scenarios 1, 2 and 3 look at the extremes in terms of CO_2 uptake, CO_2 sales and cement sales. Scenario 1, however, is the only one where the revenue is more than the cost of operations and actually has a simple payback of 15 years with oxy-combustion capture technology (Table 6). Furthermore, scenarios 1, 2 and 3 sequester sufficient CO_2 through capture and utilization to fully offset emissions and avoid paying a penalty, which for the Exshaw Cement Plant can be up to US $5 M annually. With this penalty cost avoided and considering that averaged cost values were used in this calculation, scenarios 2 and 3 may in fact be more (or less) viable. Again, these are the extreme scenarios and a hybrid of scenarios 1, 2 and 3 would likely further close this gap between capture and operation cost versus potential revenues, making carbon utilization an economically viable option.

Table 4. Summary of cost inputs

	Units	Oxyfuel Combustion Capture	Post-Combustion Capture
Capital Cost	US $M	379.32	647.28
Operating Cost w/CCS	US $M/year	94.656	150.104
Operating Cost w/o CCS	US $M/year	76.1	76.1
Capture Potential (avg)	%	83	83
Cement Pricing			
Bulk CO_2 sale (avg)	US $ /tCO_2	30.00	
Cement Sale	US $ /tonne	113.00	
Cement Product 7% CO_2 (avg)	US $ /tonne	93.00	
Cement Product 24% CO_2 (avg)	US $ /tonne	93.00	
Cost of Utilization (avg)	US $ /tCO_2	27.50	
Cost of Geologic Storage (avg)	US $ /tCO_2	52.50	
Cost of Transport	US $ /tCO_2	5.00	
Exshaw Cement Plant			
Cement Production	tonne/year	899,455.25	
CO_2 Emissions	tCO_2	769,877.68	
CO_2e Emissions	tCO_2e	772,441.06	
Threshold	tCO_2e/tonne	0.7853	
Amount above Threshold	tCO_2e	165,843.10	
Carbon Levy	US $/t$CO_2$e	23.49	
Carbon Levy Owed	US $/year	4,975,292.89	
CO_2 Capture Potential	tCO_2	638,998.47	

(IEAGHG, 2008) (Canadian Building Materials, 2018) (Jang et al., 2016)

Table 5. Summary of scenarios

Scenario 1		
100% CO_2 Sales	US $	19,169,954.14
100% Cement Sales	US $	101,638,443.70
Total	US $	120,808,397.84
Scenario 2		
CO_2 Sequestered at 7% Uptake	tCO_2	62,961.87
CO_2 remaining at 7%	tCO_2	576,036.60
Cement Product w/ 7% CO_2	US $	83,649,338.62
Cost of Utilization	US $	-17,572,457.97
Remaining CO_2 sales	US $	17,281,098.11
Total	US $	83,357,978.76
Scenario 3		
CO_2 Sequestered at 24% Uptake	tCO_2	215,869.26
CO_2 Remaining at 24%	tCO_2	423,129.21
Cement Product 24% CO_2	US $	83,649,338.62
Cost of Utilization	US $	-17,572,457.97
Remaining CO_2 sales	US $	12,693,876.32
Total	US $	78,770,756.97
Scenario 4		
CO_2 Sequestered Geologic Storage	tCO_2	638,998.47
Cost of Transport	US $	-3,194,992.36
Cost of Geologic Storage	US $	-33,547,419.75
Cost of Leakage Mitigation	US $	Unknown
Total	US $	-36,742,412.11
Scenario 5		
CO_2 Sequestered at 7% Uptake	tCO_2	62,961.87
CO_2 Sequestered at 24% Uptake	tCO_2	215,869.26
CO_2 Purchase Cost	US $	-19,169,954.14
Cost of Transport	US $	-3,194,992.36
Cost of Utilization	US $	-17,572,457.97
Cement Sales with 7% Uptake	US $	83,649,338.62
Cement Sales with 24% Uptake	US $	83,649,338.62
Total Revenue	US $	43,711,934.15
Remaining CO_2 above threshold at 7% Uptake	tCO_2	102,881.23
Remaining Carbon Levy owed	US $	2,416,267.65

(Jang et al., 2016)

Table 6. Simple payback of oxy-combustion and scenario 1

Year	Oxy-Combustion	Scenario 1
1	$473,976,000.00	$120,808,397.84
2	$568,632,000.00	$241,616,795.68
3	$663,288,000.00	$362,425,193.52
4	$757,944,000.00	$483,233,591.36
5	$852,600,000.00	$604,041,989.20
6	$947,256,000.00	$724,850,387.04
7	$1,041,912,000.00	$845,658,784.88
8	$1,136,568,000.00	$966,467,182.72
9	$1,231,224,000.00	$1,087,275,580.56
10	$1,325,880,000.00	$1,208,083,978.40
11	$1,420,536,000.00	$1,328,892,376.24
12	$1,515,192,000.00	$1,449,700,774.08
13	$1,609,848,000.00	$1,570,509,171.92
14	$1,704,504,000.00	$1,691,317,569.76
15	$1,799,160,000.00	$1,812,125,967.60

(IEAGHG, 2008)

Similarly, as with the Exshaw Cement Plant, Table 7 shows a simple calculation of the amount of CO_2 which can be sequestered for all of Canada. With cement production at 11.9 Mt and CO_2 emissions at 10.2 $MtCO_2$, using the same assumptions as above, approximately 8-28% of the total emissions from Canada's cement industry could be reduced through CO_2 utilisation in cement materials. Assumptions do include all cement produced in Canada having CO_2 injected. This assumption is not entirely realistic but does give an upper bound for the potential of emission reductions. Furthermore, with cement carbonation continuing in cement products through natural adsorption, there is additional potential for emission reductions through the life of the product.

Table 7. Extrapolation of CO_2 sequestration potential for all of Canada

Canada	**Units**	
Cement Production	tonne/year	11,900,000.00
Total CO_2e Emissions	tCO_2e	10,211,227.67
Total CO_2 Emissions	tCO_2	10,185,658.83
Capture Potential	tCO_2	8,454,096.83
CO_2 Sequestered at 7% Uptake	tCO_2	833,000.00
CO_2 Sequestered at 24% Uptake	tCO_2	2,856,000.00
Percent of CO_2 sequestered at 7% Uptake	%	8.18%
Percent of CO_2 sequestered at 24% Uptake	%	28.04%

(Government of Canada, 2016)

7.3 LIFE-CYCLE IMPLICATIONS

One area of cement carbonation not yet discussed is the life-cycle implications, more specifically the end-of-life considerations. Estimates for cement service life is approximately 70 years before demolition (Kjellsen, Guimaraes, & Nilsson, 2005). This estimate excludes cement which is buried or in wet conditions. In Denmark, 90% of demolished concrete is crushed and used as recycled aggregate in construction projects (Kjellsen et al., 2005). In Canada, millions of tonnes of aggregate has been recovered from construction sites ready to be recycled in new construction projects (OSSGA, 2018). Provincial standard specifications do not allow for recycled aggregate to be used in all projects, however efforts are being made to allow for recycling aggregates (OSSGA, 2018).

It is estimated that 75% of demolished concrete, if not already carbonated, will carbonate in 5 years due to the increased surface area (Kjellsen et al., 2005). This means that recycled concrete materials will continue to sequester CO_2 after end of life of that material. Furthermore, the CO_2 is permanently sequestered so it will not release CO_2 after its life time.

Additionally, recycling demolished concrete materials reduces the need to mine or quarry new aggregate materials.

8.0 CONCLUSIONS

Reduction of GHG emissions has been a discussion that has been evolving for the last three decades. Following the Paris Agreement in 2015 and the implementation of carbon pricing systems and penalties, reducing emissions has become an economic necessity. The cement industry is a large emitter, with approximately 5% of anthropogenic emissions coming from process emissions. As a whole, the industry is motivated to reduce its carbon footprint.

Carbon capture and storage has huge potential for large scale emission reduction. With no value added through geologic storage, carbon utilization has the potential to reduce CO_2 emissions in value added products. In the cement industry, through the process of carbonation, CO_2 can be permanently sequestered. Through this process, the microstructure of the cement become denser, making it stronger, more durable and resistant to weathering such as freeze-thaw conditions. However, limitations such as corrosion of steel reinforcements and the greatest potential for use in precast products does create challenges for the technology. Companies are finding ways around these problems, but with the technologies still in early stages of development, the scalability is not yet known.

Calculations of potential for use in the cement industry were done considering capture technologies and bulk purchase of CO_2 as well as geologic storage and utilization at different uptake levels. Some assumptions and approximations were made; however, results show utilization could have the potential to sequester 8-28% of cement industry emissions in Canada, and does appear to be economically viable, or at least could be viable given the assumptions made and potential variances in the assumptions. Carbon pricing is a driver to reduce emissions, and with prices rising to CAD \$50/tCO_2, this may promote more innovation in this

field, more subsidies to aid implementation and maybe even make this technology profitable on a large scale.

8.1 LIMITATIONS

Although the potential for CO_2 utilization in cement materials has been realized, this study is not without limitations. Many approximations and estimates were made in terms of costs and use potential. Since the technology is still emerging there is a lack of real data so, without accurate costs and pricing, this is more of a best-guess of the potentials. This includes the price for CO_2 sequestered products, with a strength and durability increase, this price could be higher. Additionally, a big assumption was made in terms of production of the cement materials on site cement manufacture plants. Although this does happen, there are many cement products, or concrete companies which could apply this technology. This scenario has not been considered in this study.

8.2 RECOMMENDATIONS AND FUTURE WORK

In addition to the limitations of the study, some things were outside the scope of this particular research paper. As potential future work for research and analysis of the scalability of this sort of technology, in terms of market potential especially due to the limits of use due to the inability to use steel reinforcements. As mentioned in the company examples, there is innovation to address this problem and future studies could be completed in this area.

As part of a discussion on reducing emissions from the cement industry, further work could be completed in terms of actual changes to the cement plant itself. This would include the use of alternate fuels, energy efficient upgrades and alternate raw materials. Additionally, the

injection of fly ash or slag into the cement products could be used as a comparison or a complementary addition. As well a study of long term CO_2 sequestration from natural CO_2 in the air could be added to the discussion on potential for CO_2 sequestration.

In this study, the focus was solely on utilization in cement materials, with some comparison to geologic storage. Further work could be done to compare cement carbonation to other emerging or established utilization technologies to better understand the potential in the field.

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