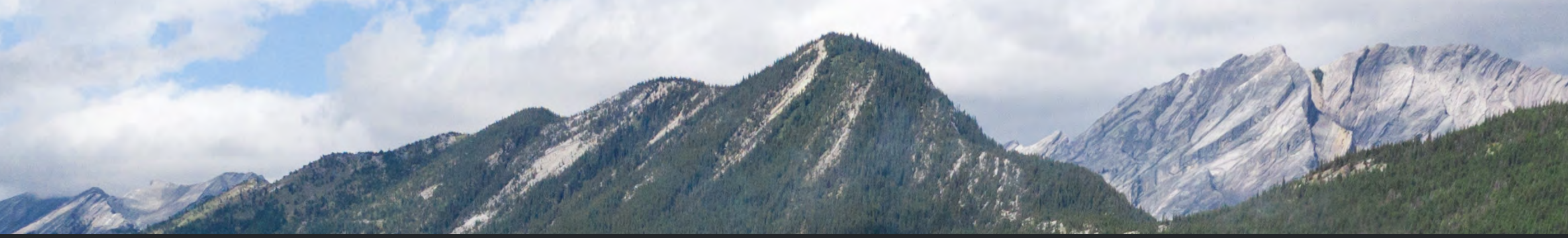
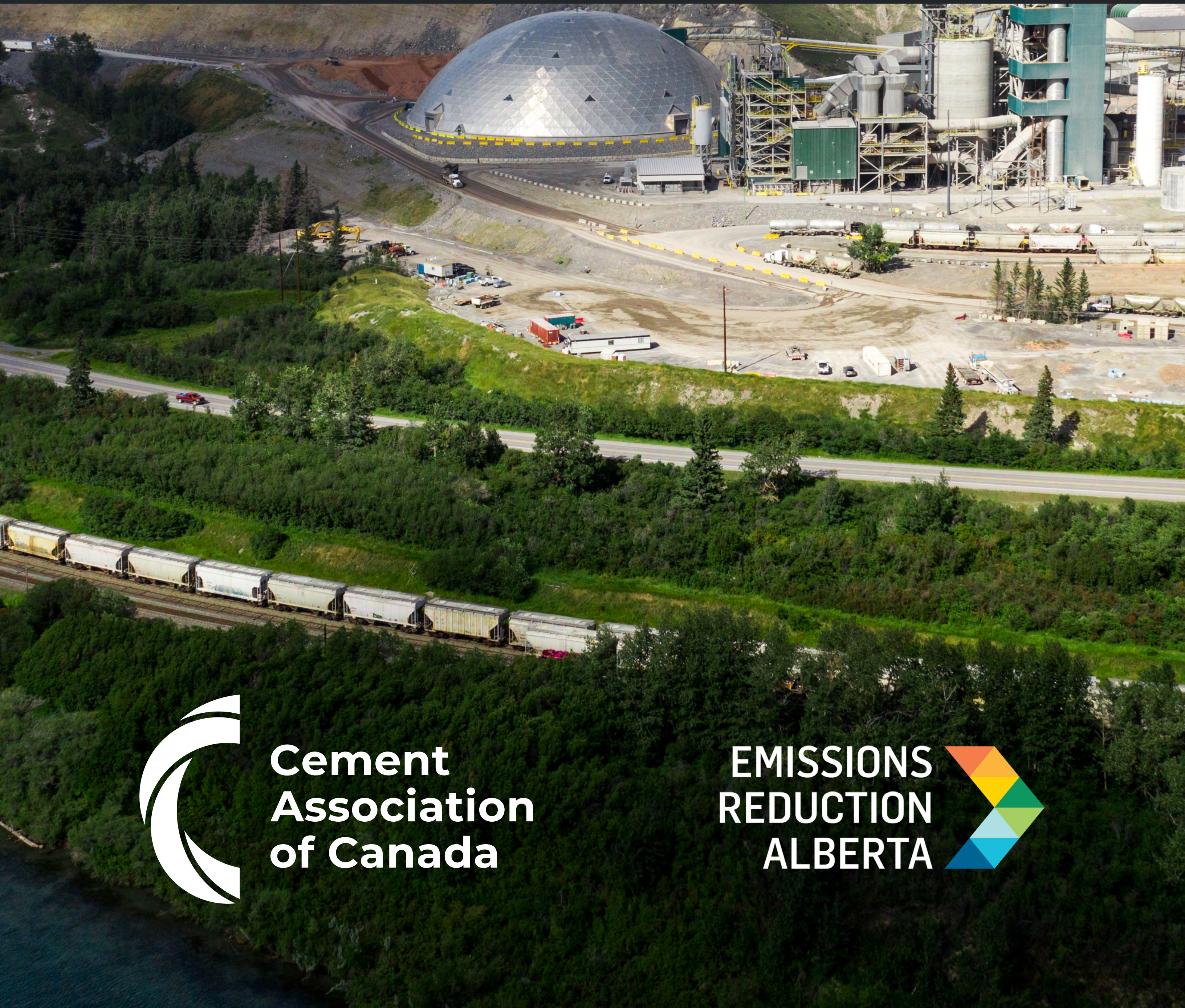


SEPTEMBER 2023

SCALING INNOVATION IN ALBERTA HEAVY INDUSTRY

10 Case Studies of Innovation & Collaboration in the Concrete Sector



Cement Association of Canada

EMISSIONS REDUCTION ALBERTA

ABOUT EMISSIONS REDUCTION ALBERTA (ERA)

ERA was created in 2009 to help deliver on the province's environmental and economic goals. Since 2009, ERA has been investing revenues from the carbon price paid by large emitters to accelerate the development and adoption of innovative clean technology solutions. These technologies will lower costs, improve competitiveness, and accelerate Alberta's transformation to a low emissions economy.

ABOUT THE CEMENT ASSOCIATION OF CANADA (CAC)

The Cement Association of Canada (CAC) is the voice of Canada's cement industry, representing five vertically integrated cement companies that provide a reliable local supply of cement to help build Canadian communities and critical infrastructure. CAC's mission is to be a transformational partner within the Canadian built environment ecosystem — one that influences, facilitates, and advances the evolution of an indispensable material to net-zero.

Heidelburg Materials Edmonton Cement Plant

CONTENTS

1.0 EXECUTIVE SUMMARY

Concrete is the world's third-largest industrial energy consumer and the second-largest industrial CO_2 emitter, representing up to 8% of CO_2 emissions globally and 1.4% in Canada. Turning concrete into a net zero industry is a critical piece of mitigating climate change. The Canadian concrete industry has a history of innovation in the context of changing market forces, and technologies exist today to fully decarbonize this sector within our lifetimes – without the use of offsets.

The province of Alberta is home to a healthy concrete industry that supports 39,000 jobs and contributes $16B annually to Alberta's economy. It is also home to the Technology Innovation Emissions Regulation (TIER), a carbon pricing system that enables reinvestment of industrial carbon tax into emissions reduction technologies through Emissions Reduction Alberta (ERA). Over the past decade, ERA has invested $70M in concrete decarbonization projects and more than $160M in carbon capture, utilization, and storage (CCUS) technologies now being implemented across the concrete sector.

Recently, in collaboration with industry partners, the Cement Association of Canada (CAC) published a net zero roadmap called Concrete Zero, which organizes emissions reduction opportunities for the industry across five "C's": **clinker, cement, concrete, construction,** and **carbon uptake**. Technologies supported through ERA and the TIER fund over the past decade provide real case studies of net-zero compatible technologies currently being deployed across the five C's. Many of them also demonstrate significant circular economy opportunities to valorize waste. These projects have led to collaborations with other provinces and countries, like pilots in neighboring BC and testing in U.S. laboratories, as well as partnerships with other sectors, such as power plants and transportation.

ERA and CAC have jointly prepared a summary of **ten case studies of innovation and collaboration in the concrete sector** supported by ERA and the TIER fund over the past ten years. Altogether, they total $70M of investment, $275M+ total project value, with over 2.2Mt CO_2e direct emissions reductions by 2030 and an even greater number of enabled reductions as technologies are rolled out across the market. While this list is by no means comprehensive, these case studies are all viable decarbonization pathways across the five "C's" being demonstrated in Alberta today. Together, show how the industry is addressing most, if not all, emissions reductions pathways and exemplify the technology leadership of Canada's heavy industry.

Technologies like fuel switching and carbon capture are available in the near term to reduce emissions from clinker production, the most carbon-intensive part of making concrete. Carbon capture is currently the biggest available lever for emissions reduction, but remains high-cost, high-footprint, and energy intensive. Therefore, any technology that can reduce the amount of CO_2 to be captured or make it easier to capture can greatly improve capture economics. Other near-term options to reduce concrete emissions include increasing use of supplementary cementing materials (SCMs), improvements to end of life concrete management, and overall enhancements to the concrete circular economy.

In the mid to long term, novel, improved carbon capture technologies and process innovations can improve the economics of capture. Carbon utilization may also play a greater role. Additionally, alternative forms of cement production may become viable, and these can further reduce the cost of getting to net zero concrete and in some cases avoid emissions altogether.

While these ten case studies demonstrate that technology is advancing, an important aspect of the concrete sector is that the government is largest consumer of these products for core social infrastructure, such as roads, bridges, and buildings. This creates both challenges and opportunities in terms of technology transfer and deployment, since concrete is subject to numerous regulations from the national to the local level, and cement, its core component, is an internationally traded product. Continued collaboration between CAC, ERA and other stakeholders across the value chain can help de-risk innovation to reach full commercial implementation.

Importantly, lessons learned from the Alberta concrete sector and innovation ecosystem are transferable to other industrial sectors. Case studies such as the projects supported by ERA and Alberta's industry can further position the Canadian concrete industry as global leaders in climate change mitigation.

TECHNOLOGY ROADMAP FOR THE CONCRETE SECTOR

Available today or in <1 year: Alternative kiln fuels, supplementary cementing materials, and improved end of life concrete management

Available in <5 years: Large-scale carbon capture, improvements to capture economics

Available in 5-10 years+: Next generation carbon capture technologies and process innovations, carbon utilization, and novel cement production


Lafarge Exshaw Cement Plant

TECHNOLOGY	PROJECT	TRL*	TIME TO FULL COMMERCIAL SCALE	EMISSIONS REDUCTION POTENTIAL**
CLINKER: The primary ingredient of cement. Clinker is produced by heating limestone, clay, and other minerals in a rotary kiln system to about 1500 °C.				
Alternative low carbon fuels from used tires, construction materials, and, municipal waste	Implementation at Lafarge Exshaw & Heidelberg Edmonton Cement Plants	9	<1 year	Currently 10%, up to 30% in the future
Full-scale carbon capture, utilization, and storage	FEED at Heidelberg Edmonton and Lafarge Exshaw Cement Plants	9	<5 years	Up to 80% (95% capture efficiency)
Novel capture technologies	Svante's solid sorbent capture technology pilots & FEED studies	6-7	5-10 years	Up to 80% (95% capture efficiency)
CEMENT: The active ingredient in concrete, comprising about 10% of a concrete mix.				
MgO-based cement	Pilot scale testing by ZS2 Technologies	5-6	10 years+	70%
Electrification of cement production	Pilot scale testing by CarbonCorp	3-4	10 years+	60%
CONCRETE: The castable, stone-like, composite building material comprised of fine and coarse aggregates bound together with water and cement that hardens over time.				
Landfill fly ash beneficiation	Implementation by Lafarge at Transalta power plant site	9	<1 year	10%
CO_2-enhanced fly ash (carbon utilization)	Carbon Upcycling Technology pilots at Burnco in Calgary and Transalta outside of Edmonton	6-7	<5 years	15%
CONSTRUCTION & CARBON UPTAKE: The use of concrete products in the infrastructure around us. An average of 20% of the CO_2 in the process emissions from clinker production can be permanently sequestered when a concrete structure is built, and surfaces are left exposed to the atmosphere.				
Carbon nanotube-enhanced concrete	Pilot testing by CarbonCorp and initial production at Capital Power Genesee Carbon Conversion Centre	7-8	5-10 years	Up to 30% enabled reductions
Soil & concrete recycling, reuse as raw clinker material	Calgary Aggregate Recycling soil reuse facility, waste clay pilot for raw material at Lafarge Exshaw	9	<1 year	Enabled reductions

*Technology Readiness Levels (TRLs). See https://www.canada.ca/en/department-national-defence/programs/defence-ideas/technology-readiness-level.html.

**Emissions reduction potential: Provided in terms of the entire concrete sector.

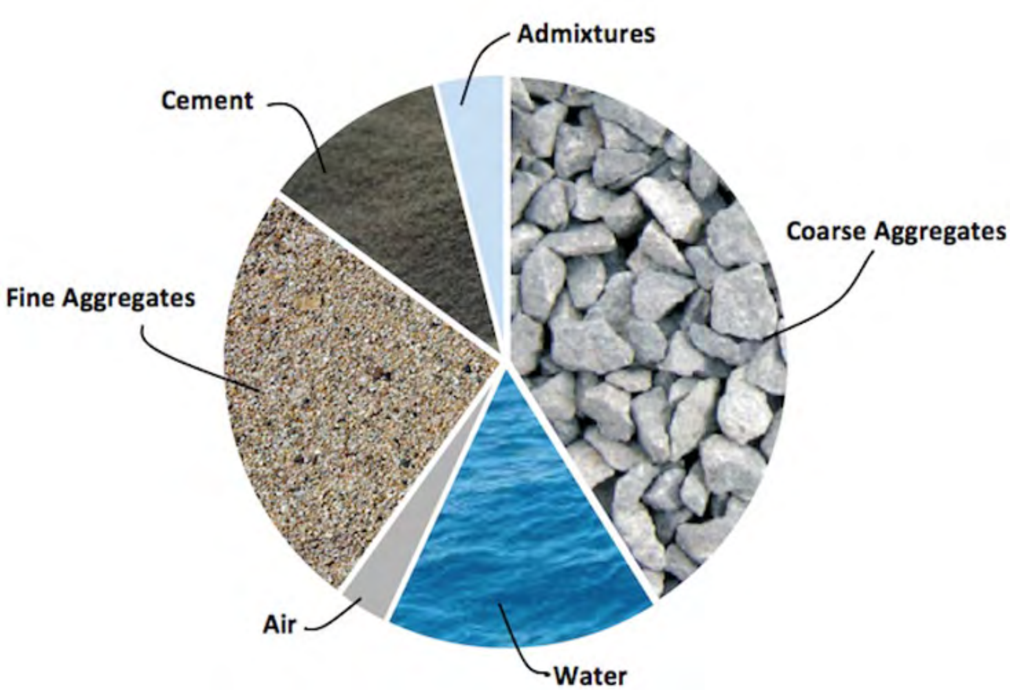
2.0 INTRODUCTION

Nationally, Canada has set a target to reach a net zero grid by 2035 and net zero across all sectors by 2050. As a source of 8% of global emissions, the concrete sector must be part of the solution. Concrete is the world's most ubiquitous construction material, used twice as much all other construction materials combined. Because of the way it's made, concrete has the unique ability to tap into the entire value chain of carbon capture, utilization, and storage (CCUS). Concrete production also offers multiple avenues for circular economy solutions through valorization of waste. All these factors contribute to concrete's potential to become a carbon negative industry in the not-so-distant future.

The Cement Association of Canada's Concrete Zero roadmap calls on the concrete sector to reduce emissions by up to 40% by 2030, 67% by 2040, and achieve complete net zero by 2050 across the five C's of concrete emissions management: clinker, cement, concrete, construction, and carbon uptake. Through the TIER fund, ERA has supported $70M in technology deployment across the five C's that are now being implemented and scaled up in Alberta and a total of >2.2 $MtCO_2e$ in direct emissions reductions. In the following sections, we describe ten case studies of concrete innovation and collaboration happening today. While these are not comprehensive, they represent compelling examples of possible pathways to Concrete Zero.

Diagrams and statistics in this paper related to the concrete sector have been provided by the Cement Association of Canada. Technology and facility photos have been provided by ERA and project proponents.

Figure 3-1 Diagrammatic Representation of Typical Concrete Constituents



3.0 CONCRETE ZERO

In this section, we discuss the making of concrete and cement, and their respective contributions to global emissions. Then we describe the Canadian industry's pathway to net zero and the five C's: clinker, cement, concrete, construction, and carbon uptake.

3.1 CONCRETE

At the most basic and fundamental level, concrete is a mixture of materials, most notably cement, gravel, sand, and water. To simplify, it can be thought of as aggregate and paste. The aggregate component is normally comprised of the sand and gravel. The paste component, also known as cement, is comprised of the materials with pozzolanic or glue-like properties. Due to its weight, concrete is typically used within 160 kilometers of where it's produced.

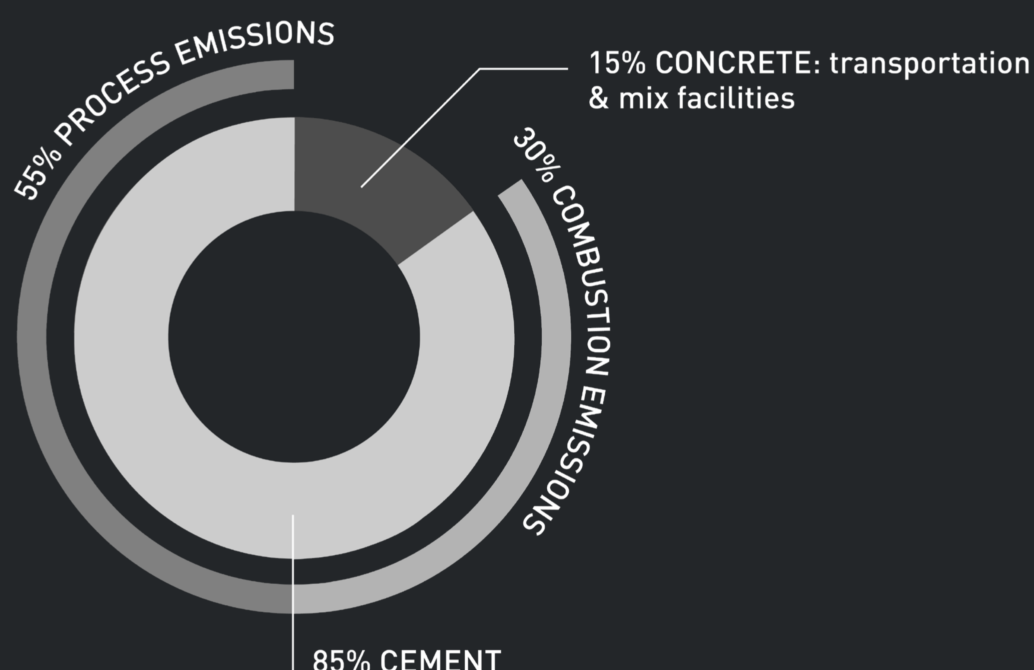
Figure 3-1 illustrates the materials that constitute a given batch of typical concrete. The amount of each constituent varies depending on the mix design.

WHAT IS CONCRETE USED FOR?

More than 40% of concrete is used by the government for public infrastructure.

- Public buildings, like schools and hospitals
- Power and energy
- Transportation
- Water
- Telecommunications
- Parks and recreation

Figure 3-2: Diagrammatic Representation of Typical Concrete Constituents



3.2 CEMENT

Cement is the paste, or glue, that binds aggregate materials together to form concrete. While cement only composes about 10% of concrete by volume, it is by far the most emissions-intensive component, accounting for approximately 85% of concrete's emissions footprint. Therefore, reducing the emissions associated with cement will have a significant impact on the embodied carbon in concrete.

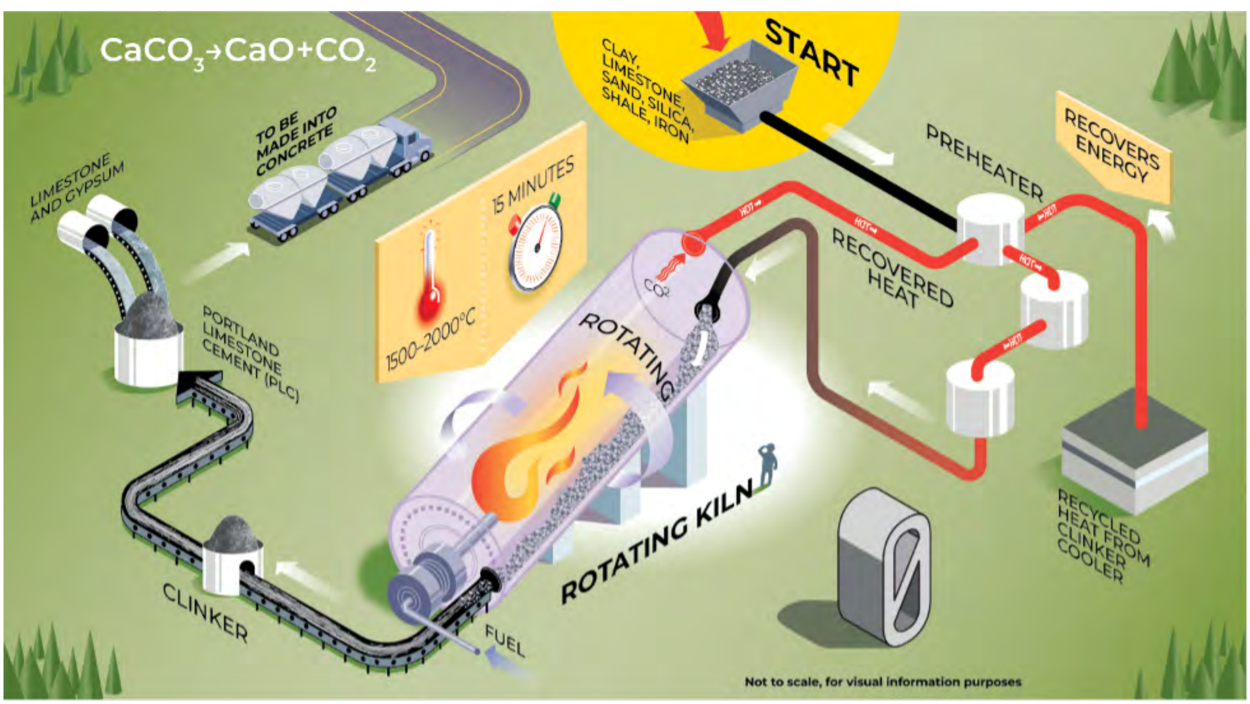
The manufacture of cement involves grinding raw materials of limestone, clay, sand, silica, and iron together in certain proportions and subjecting them to intense heat within a rotary kiln. The material sinters and forms balls known as clinker. The clinker is cooled and ground to a fine powder and mixed with some ground gypsum. The resulting product is known as Portland cement, a name given to the hardened concrete produced, which shares characteristics with the original limestone quarried in Dorset, United Kingdom during the early days of the concrete industry.

Figure 3-3 depicts a typical dry cement manufacturing process.

Emissions in the cement making process arise from two main sources:

1. **The energy required to heat the kiln to make the cement,** which traditionally comes from combustion of fossil fuels, and accounts for 30-40% of cement emissions, or **25-35% of total concrete sector emissions**; and
2. **The chemical reaction that occurs within the kiln**, the separation of the CO_2 from the raw materials, accounting for the remaining 60-70% of cement emissions, or **50-60% of total concrete sector emissions**.

Figure 3-3 Generic Cement Manufacturing Process



One of the most straightforward ways to reduce emissions from cement is migration away from fossil fuels for kiln combustion and replacing these with more sustainable energy sources that have sufficient heat value to maintain cement kiln operations. The process emissions associated with the chemical reaction that occurs during the cement making process are more difficult to abate, but industry is working to address these emissions as well.

Of note, while concrete is inherently a local product due to its weight, cement is a commodity subject to the global trade environment.

3.3 CANADA'S INDUSTRY: CONCRETE ZERO

Canada's cement and concrete industry is an important driver of our national economy. Across Canada, there are 15 cement plants shipping cement to more than 1,100 associated facilities that produce a variety of precast concrete products, ready mixed concrete, concrete pipe, and concrete masonry. Collectively, the industry supports about 166,000 direct and indirect jobs across the country, and contributes $76 billion dollars in annual direct, indirect, and induced economic benefit to the Canadian economy. Figure 3-4 shows the economic breakdown by region in Canada.

The Cement Association of Canada and industry partners recently released Concrete Zero, an action plan to reduce emissions by up to 40% by 2030, 67% by 2040, and achieve complete net zero by 2050. A key aspect of the plan is that the industry will reduce CO_2 emissions without the purchase of offsets.

Concrete Zero is organized around the cement and concrete value chain and identifies where emission reductions will come from at each stage. Industry refers to these stages as the "5 C's".

Figure 3-4 Economic Impact of Concrete Industry in Canada

THE 5 C'S	DESCRIPTION	TECHNIQUES TO REDUCE EMISSIONS
CLINKER	The primary ingredient of cement. Clinker is produced by heating limestone, clay, and other minerals in a rotary kiln system to about 1500 °C.	+ **Alternative low carbon fuels** to displace fossil fuels used to heat the kiln, thereby reducing combustion emissions + **Displacement of clinker** with less carbon-intensive materials in cement + **Carbon, capture, utilization and storage** of the inherent process emissions.
CEMENT	The active ingredient in concrete, comprising about 10% of a concrete mix.	+ **Adjusting cement blends** to reduce process emissions + **Deploying next generation cement production methods** that reduce or avoid process emissions altogether.
CONCRETE	The castable, stone-like, composite building material comprised of fine and coarse aggregates bound together with water and cement that hardens over time.	+ **Mix optimization**, such as displacing cement with supplementary cementing materials (SCMs). + Powering concrete mixing facilities and transport trucks with **clean energy**.
CONSTRUCTION	The use of concrete products in the infrastructure around us.	+ **Design optimization** to limit overdesign without compromising safety + **Waste reduction** on the job site to decrease hauling emissions and avoid contributions to landfills.
CARBON UPTAKE	An average of 20% of the CO_2 in the process emissions from clinker production can be permanently sequestered when a concrete structure is built and surfaces are left exposed to the atmosphere.	+ **End of life concrete management**. With proper techniques, demolished concrete can sequester an additional 2% of process emissions. A further 1% is permanently sequestered if the demolished concrete is reused as an aggregate. + **Recycling concrete** and enhancing the circular economy can avoid the need to obtain to extract new materials.

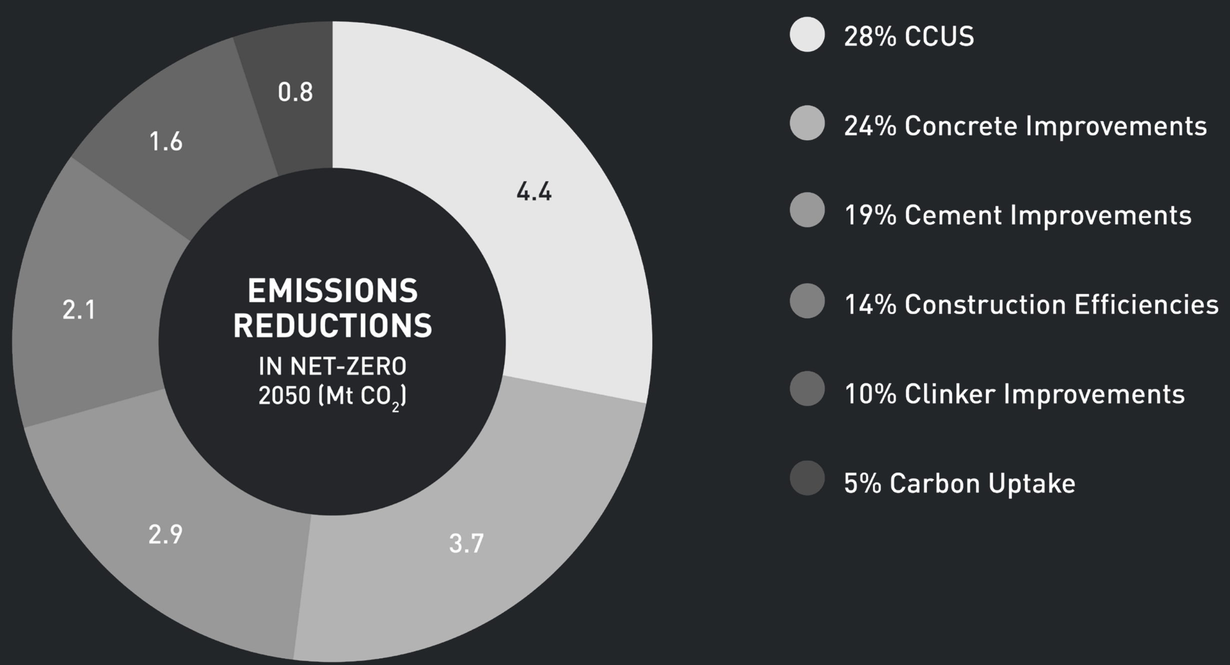
One of the key cross-cutting technology pathways that will enable the cement industry in Canada to reach net-zero is **carbon capture, utilization, and storage (CCUS).** CCUS is vital to eliminate both process and combustion emissions in cement production. Most cement plants exploring CCUS at commercial scale intend to sequester captured CO_2 in geologic formations. This is especially true in jurisdictions where suitable geologic pore space is readily available, such as Alberta.

One of the unique aspects of the cement and concrete sector is its ability to also utilize some of the CO_2 it produces, or even utilize CO_2 produced by other industries. Not only does concrete naturally act as a carbon sink over its lifetime, but captured CO_2 can be embedded in the concrete-making process in other ways to reduce its overall carbon footprint. Utilization technologies are significantly more complex and less mature than than geological sequestration. They nevertheless may offer a niche solution to cement plants and other emissions sources located in jurisdictions where suitable pore space is not available or is too expensive. Unlike pure sequestration, carbon utilization has the follow-on benefits of new value generation and economic development opportunities.

Figure 3-5 shows the relative percentage reductions of emissions resulting from the 5 C's, as well as the reduction contribution from CCUS. The numbers within the pie chart wheel represent the megaton CO_2 reductions from the base year 2020 to net-zero year of 2050. The importance of CCUS is apparent, and industry has made significant strides, including plans to have full scale CCUS deployed at cement manufacturing facilities in Alberta well before 2030.

When all these emissions reduction approaches are used in combination, it will be possible to turn what is currently the source of 8% of the planet's emissions into a carbon-negative industry within our lifetimes and without the use of offsets.

Figure 3-5 Concrete Zero Emission Reduction Areas of Focus



3.4 CURRENT INDUSTRY TRENDS

The Canadian concrete industry has a strong track record of deploying new technologies and problem-solving in response to market changes. One key example is implementation of Portland Limestone Cement (PLC) over the past two decades. PLC entails replacement of 5% of cement in concrete with ground limestone, resulting in a lower-emissions profile, but equivalent concrete product. Despite some challenges to deployment, PLC has reached widespread commercial use and has become the new benchmark for reducing emissions in the North American concrete industry.

Another, more recent example of successful transition in the cement and concrete sector is related to the disappearance of fly ash. Known as a supplementary cementing material (SCM), fly ash is an important component of concrete that was traditionally sourced as a byproduct from coal plants. With the shutdown of coal plants in many jurisdictions across Canada, the industry has seen initial success in seeking new sources of fly ash and substituting alternative aggregate materials.

In line with the Concrete Zero roadmap, cement plants across Canada are targeting staged emissions reductions over the next three decades to reach net zero by 2050. The **ten case studies outlined in Section 5 of this paper** build on the above examples to demonstrate a viable pipeline of new technologies for Alberta's concrete sector, with globally applicable lessons learned.

Lafarge Exshaw was constructed in 1906 and now operates with updated facilities using best available technology. It is the largest cement plant in Canada and serves markets across Western Canada and the Pacific Northwestern US.

Heidelberg Materials' Edmonton Cement Plant (pictured above), which was build in 1956 and modernized in 1980, and is set to become the world's first net zero cement plant through implementation of CCUS.

4.0 ALBERTA CONTEXT

In this section we provide some brief information on the Alberta context for Concrete Zero.

4.1 CONCRETE MANUFACTURING IN ALBERTA

The province of Alberta is home to a healthy concrete industry that supports 39,000 jobs and contributes $16B to Alberta's economy. Alberta is home to two major cement plants – the Lafarge Exshaw Cement Plant between Banff and Calgary and the Heidelberg Materials facility in Edmonton – as well as 150 ready-mix and associated facilities within the concrete value chain.

The Alberta concrete industry is responsible for approximately 2% of the province's emissions and produces approximately 2.5MT cement/year, which goes into about 12.5MT concrete. Saskatchewan and Manitoba do not have their own cement manufacturing facilities, therefore a portion of cement produced in Alberta is exported out of provinces, as well as the US.

4.2 ALBERTA'S CARBON PRICING SYSTEM

Alberta has a robust infrastructure in place for managing and reducing emissions from the concrete sector. The province is home to the [Technology Innovation Emissions Regulation (TIER)] that implements Alberta's industrial carbon pricing and emissions trading. Under TIER, emitters can reduce on-site emissions, submit offset credits, submit performance credits, or purchase fund credits by paying into the TIER fund. TIER sets high standards for compliance without threatening local employment or the economy and provides a continuous incentive for industrial facilities to refine operations. Each year, a portion of the TIER fund is reallocated to emissions reduction technology & innovation investment.

4.3 EMISSIONS REDUCTION ALBERTA

Emissions Reduction Alberta (ERA) is a technology funding organization created in 2009 to deliver on the province's environmental and economic goals. ERA takes action on climate change and supports economic growth by investing in the pilot, demonstration and deployment of clean technology solutions that reduce emissions, lower costs, attract investment, and create jobs in Alberta, by reinvesting contributions from the TIER fund.

To date, ERA has invested almost $900M on over two-hundred emissions reduction projects in Alberta spanning many different sectors and technologies. Of this, ERA has invested $70M with a total value of $275M+ on scale-up projects across the entire concrete value chain that, in partnership with ongoing work in other provinces, can help pave the way for Canada's Concrete Zero goal.

In addition, over the past decade, Alberta Innovates and ERA have collectively provided more than $160M in funding towards CCUS innovation. Projects range from engineering studies, technology pilots to capture CO_2 and transform it into highly valuable products, novel carbon capture technologies to reduce cost and improve capture rates, and support for sequestration and enhanced oil recovery feasibility analyses. A number of CCUS technologies supported by the province are targeting deployment in the concrete sector, with some reaching commercial implementation in the near term.

5.0 PROJECT CASE STUDIES

Ten project case studies supported by ERA through industrial carbon tax on Alberta's heavy emitters demonstrate tangible progress towards the industry's Concrete Zero roadmap. Some are competing technologies; others are parallel pathways. Virtually all of the following case studies are applicable across Canada and worldwide. Some have already resulted in technology transfer and scale up opportunities in other sectors, provinces, and countries.

Where applicable, we have noted opportunities for future work, as well as relevant parallel activities we are aware of taking place in other jurisdictions. Of note, many of these technology pathways offer not only emissions reductions, but also present circular economy opportunities to valorize and reduce waste.

A note on emissions reductions: For each case study, we have calculated the emissions reduction potential of the technology in terms of how it addresses emissions across the **entire concrete sector**. For example, a carbon capture technology installed at a cement plant capable of a 95% capture rate would have the potential to reduce up to around 80% of overall concrete sector emissions, since cement emissions account for 85% of total concrete sector emissions. In some cases, emissions reductions are enabled, meaning there is no standardize method of calculating the exact reductions, but they will result in downstream emissions benefits. Where possible, we've tried to quantify this.

5.1 CLINKER

The following case studies are examples of decarbonization pathways for clinker.

CLINKER	The primary ingredient of cement. Clinker is produced by heating limestone, clay, and other minerals in a rotary kiln system to about 1500 °C.	**Techniques to reduce emissions:** **Alternative low carbon fuels** to displace fossil fuels used to heat the kiln, thereby reducing combustion emissions **Displacement of clinker** with less carbon-intensive materials in cement **Carbon, capture, utilization and storage** of the inherent process emissions.

CASE STUDY #1: LAFARGE & HEIDELBERG MATERIALS ALTERNATIVE LOW CARBON FUELS IMPLEMENTATION

OVERVIEW: Both of Alberta's cement plants are installing systems and infrastructure to replace 30-50% of fossil fuels used in their cement kilns with alternative fuels from multiple waste streams that would otherwise be landfilled. This in turn reduces emissions from clinker production in cement and landfill gas emissions. Alternative fuel types are derived from construction renovation and demolition waste, municipal solid waste, non-recyclable plastic and packaging waste, carpet and textiles, shingles, treated wood products, residual tire fiber, and other waste streams with combustible components.

TRL: 9	**EMISSIONS REDUCTION POTENTIAL:** Currently 10%, up to 30% in the future	**LOCATION:** Lafarge Exshaw & Heidelberg Edmonton Cement Plants
COMBINED PROJECT VALUE: $70M	**COMBINED ERA FUNDING:** $12.3M	**TIME TO FULL COMMERCIAL SCALE:** Entering commercial operations now

KEY BENEFITS: Reduced emissions from fossil fuel combustion, diversion of waste and reduced emissions from landfill. Fuel flexibility can also reduce cement plants' exposure to fuel price changes. Cement kilns are versatile in terms of the type of fuel they can consume, providing an elimination pathway for multiple waste streams in other sectors.

KEY CHALLENGES: Unlike coal and natural gas, alternative waste streams are inherently non-uniform, which means their heating value is not uniform, either. This creates operational complexities to maintain consistent heating value in the kiln. Lafarge and Heidelberg are overcoming these challenges via these ERA-supported projects.

FUTURE WORK OPPORTUNITY

Alternative low carbon fuels can displace an increasing percentage of fossil fuels over time. Beyond fuels from waste streams, some cement plants are considering hydrogen booster fuel. While hydrogen presents challenges as a cement kiln fuel by itself, when used as a booster, it can improve efficiency of co-processing with waste-based fuels.

CASE STUDY #2: HEIDELBERG MATERIALS EDMONTON FIRST-OF-A-KIND CCUS PROJECT

OVERVIEW: In partnership with the Governments of Canada and Alberta, Heidelberg Materials plans to host the first full-scale CCUS solution for the cement industry globally at its Edmonton Cement Plant. Heidelberg anticipates that CCUS will be operating by late 2026 and will capture and store more than 1 $MtCO_2$ annually from the cement kiln and integrated combined heat and power facility. As part of their approach, Heidelberg is integrating combined heat and power to reduce the overall levelized cost of capture and provide supplemental low-carbon power to the grid. The project will also capture and store biogenic CO_2 that is produced when alternative low carbon fuels are used to heat the Edmonton cement kiln, thereby removing CO_2 from the atmosphere as well avoiding emissions.

In August 2023, to further de-risk full-scale CCUS, Heidelberg Materials announced that Mitsubishi Heavy Industries, Ltd. (MHI) delivered and installed a compact liquid amine CO_2 pilot capture system "CO_2MPACT™" at its cement plant in Edmonton, Alberta, Canada.

TRL: 9	**EMISSIONS REDUCTION POTENTIAL:** Up to 80% (95% capture efficiency)	**LOCATION:** Heidelberg Materials Edmonton Cement Plant

TIME TO FULL COMMERCIAL SCALE: Heidelberg is currently in the late stages of FEED, aiming to reach FID in 2024 and begin capturing and sequestering up to 95% of the CO_2 from the Edmonton Cement Plant in 2026. This builds on an initial feasibility study supported by ERA in early 2022.

CASE STUDY #3: LAFARGE EXSHAW CCUS PROJECT

OVERVIEW: Lafarge Canada Inc. is assessing the technical and economic feasibility of CCUS at their Exshaw Cement Plant, a visible landmark on the highway between Calgary to Banff. The project includes considerations for a transportation network and sequestration hub that will have the ability to link multiple industrial capture sites to form a CO_2 network in the Bow Valley region.

TRL: 9	**EMISSIONS REDUCTION POTENTIAL:** Up to 80% (95% capture efficiency)	**LOCATION:** Lafarge Exshaw Cement Plant

TIME TO FULL COMMERCIAL SCALE: Lafarge is currently in the feasibility stages and plans to enter FEED in 2024. Lafarge is targeting FID in 2026 and reaching full commercial operations by 2030.

PARALLEL PATHWAY

Lafarge is also exploring utilization pilots in the neighboring province of BC, including a CO_2 to fuels opportunity with Dimensional Energy and a pilot of Svante's novel solid sorbent capture technology (See Case Study #4).


Lafarge Exshaw Cement Plant

WHY IS CCUS SO IMPORTANT?

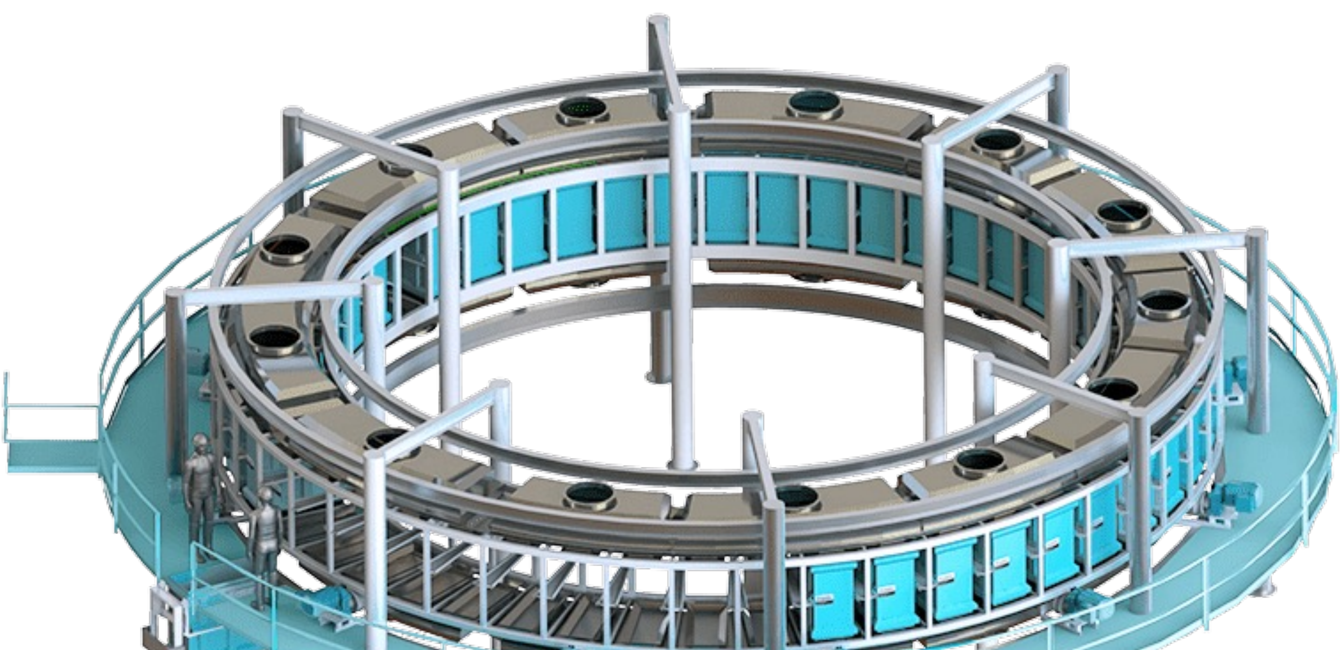
At full commercial scale, CCUS enables near-elimination of process and combustion emissions during the production of clinker. When used in combination with other emissions reduction technologies, CCUS allows the possibility of carbon negative cement and concrete. First-movers to deploy CCUS will be able to de-risk this technology pathway for heavy industry worldwide and demonstrate Canada's global climate leadership.

Significant challenges remain to deploy CCUS more broadly. CCUS relies on a robust carbon pricing and policy infrastructure. Commercially available liquid amine carbon capture is capital-intensive to deploy. It is also an energy-intensive chemical process with a significant land footprint. As CCUS is rolled out across more facilities and industries, lower cost, less energy intensive, and higher performing capture technologies will be increasingly required. Just as essential will be process innovations to reduce the amount of CO_2 produced in the first place or make it easier to capture.

Of course, capturing CO_2 alone is not enough: emissions must be permanently removed from the atmosphere to abate climate change. Access to geological pore space is a requirement for permanent carbon sequestration. In Alberta, pore space is readily available, and a process is being implemented for it to be thoroughly assessed for safety & permanence. Sequestration has the downside in that no new value is generated, and thus implementation relies on appropriate carbon pricing policies.

Carbon utilization, such as conversion to nanomaterials or embedding CO_2 in cementitious materials, can generate new value and economic activity from captured CO_2 – but significant challenges in scaling, economics, and infrastructure remain. Utilization will make the most sense for applications where geological pore space is not available or too expensive, and there is nearby access to a significant CO_2 end-user, such as in the case of Lafarge's pilot project with Svante and Dimensional Energy.

CASE STUDY #4: SVANTE VELOXOTHERM SOLID-SORBENT CARBON CAPTURE TECHNOLOGY		
OVERVIEW: Svante was formed in Alberta in 2007 and is now commercializing a post-combustion CO_2 capture technology targeting cement kilns where clinker is made. This will offer a compelling alternative to commercially available liquid amine capture technology. Svante uses pretreatment technology to reduce particulates and a Metal Organic Framework (MOF) adsorption process to purify the CO_2 to >95%. Svante has multiple pilots and FEED studies underway across Canada and the US and is constructing a new manufacturing facility in Vancouver for their core solid-sorbent technology.		
TRL: 6-7	**EMISSIONS REDUCTION POTENTIAL:** Up to 80% (95% capture efficiency)	**LOCATION:** Active: Multiple pilots in BC & SK
PROJECT VALUE: $37.8M	**ERA FUNDING:** $12.3M	**TIME TO FULL COMMERCIAL SCALE:** Svante aims deploy at scale by 2025, with full commercial rollout over 5-10 years.
KEY BENEFITS: High capture rates in flue gas with high particulate content. Opportunities for supply chain diversification, smaller footprint, and lower capex over conventional liquid amine technology.	**KEY CHALLENGES:** While Svante is operating several pilots, more data and greater scaling is needed to de-risk full-scale CCUS projects.	



5.2 CEMENT

The following case studies demonstrate examples of decarbonization pathways for cement.

CEMENT	The active ingredient in concrete, comprising about 10% of a concrete mix.	**Techniques to reduce emissions:** **Adjusting cement blends** to reduce process emissions **Deploying next generation cement production methods** that reduce or avoid process emissions altogether.

CASE STUDY #5: PROJECT PRAIRIE SEAWATER FOR GREENER CEMENT

OVERVIEW: ZS2 Technologies has developed a next generation cement production method to produce Magnesium-based cement (MBC) as a greener alternative to Portland cement. Their MBC process combines post-combustion-captured CO_2 with magnesium from off-spec ore and calcium recovered from local residual brines produced during lithium or oil extraction. MBC therefore both directly sequesters CO_2 and displaces CO_2-intensive conventional cements.

TRL: 6	**EMISSIONS REDUCTION POTENTIAL:** 70%	**LOCATION:** Multiple in Alberta
PROJECT VALUE: $6.5M	**ERA FUNDING:** $2M	**TIME TO FULL COMMERCIAL SCALE:** 10+ years.

KEY BENEFITS: Circular economy opportunity to valorize waste streams from lithium or oil and gas industries. Technology addresses multiple opportunities: alternative cement chemistries, carbon utilization, green building materials, and lithium production.

KEY CHALLENGES: Currently MBC is a niche market. This is a mid to long term opportunity at full scale, as it will require replacement of much of the existing value chain. Other challenges include technology de-risking, process optimization, value chain optimization, and access to clean electricity.

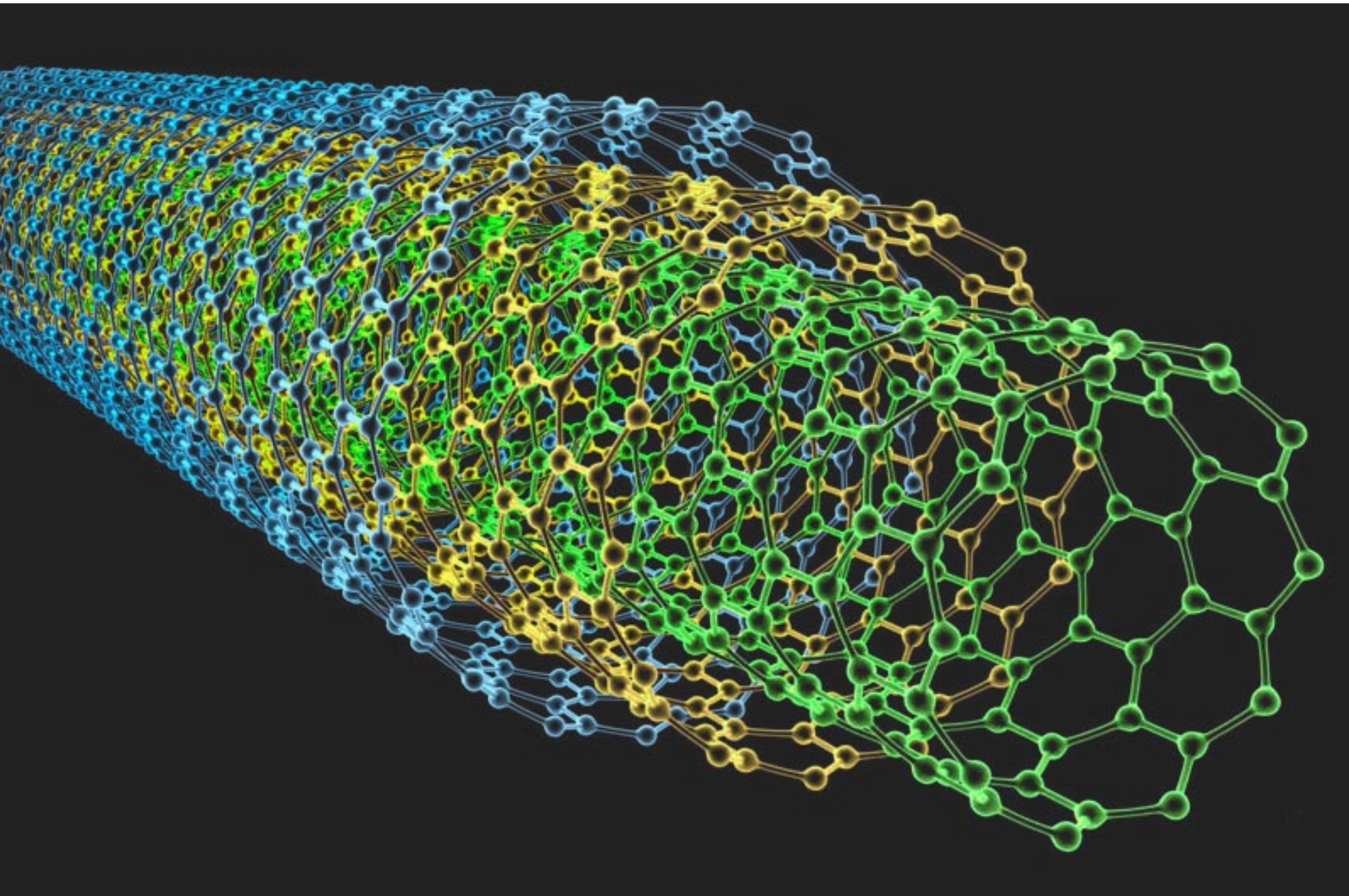
PARALLEL PATHWAY

Lafarge is exploring the use of recycled glass as an alternative pozzolanic material in Kamloops, BC and has formed an MOU with Progressive Planet. This project entails taking recycled glass and turning it into a cementitious material that Lafarge will purchase if it meets specifications. This project has opened up collaborations between different industries in BC.

CASE STUDY #6: CARBONCORP ELECTROLYTIC CEMENT PRODUCTION		
OVERVIEW: Carbon Corp has developed a next-generation cement technology that co-produces lime (calcium oxide, or CaO), a core component of cement, as well as valuable carbon nanomaterials using captured CO_2 as a feedstock. In the future, this technology could enable a new pathway for a zero-emissions cement production process while also introducing carbon nanomaterials to cement, leading to enhanced strength materials.		
TRL: 3-4	**EMISSIONS REDUCTION POTENTIAL:** 60%	**LOCATION:** Multiple in Alberta
PROJECT VALUE: $10M	**ERA FUNDING:** $5M	**TIME TO FULL COMMERCIAL SCALE:** 10+ years.
KEY BENEFITS: 1:1 replacement for cement that can be completely emissions free by avoiding process emissions altogether, while also producing a valuable CNT byproduct.	**KEY CHALLENGES:** Scalability, technology readiness, time to market, and access to clean electricity. This is a mid to long opportunity.	

PARALLEL PATHWAY

Electrification could open up new avenues for cement decarbonization. Heidelberg Materials is working on a different cement electrification technology called "LEILAC" in Europe, which is TRL 3-4. LEILAC decouples the pre heating from the kiln and provides indirect heat to calcine the limestone. This creates a very pure stream of CO_2 that's much easier to capture.



5.3 CONCRETE

The following case studies demonstrate examples of decarbonization pathways for concrete.

CONCRETE	The castable, stone-like, composite building material comprised of fine and coarse aggregates bound together with water and cement that hardens over time.	**Techniques to reduce emissions:** **Mix optimization**, such as displacing cement with secondary cementitious materials, like fly ash. Powering concrete mixing facilities and transport trucks with **clean energy**.

CASE STUDY #7: LAFARGE LANDFILL FLY ASH BENEFICIATION		
OVERVIEW: Fly ash, a byproduct of coal plants, is a supplementary cementing material (SCM) that can lower the embodied carbon of concrete. Over the years, not all the fly ash produced by coal plants was used in concrete, and much of it was disposed of in landfills. Given the shift away from coal-fired power plants in Alberta resulting in fresh fly ash ceasing to be produced since end of 2021, Lafarge aims to reclaim landfilled fly ash and use it as an SCM for concrete production. This project uses patented technology to "beneficiate" landfilled fly ash material to meet regulatory and market standards. Lafarge has formed a partnership with Transalta, a former coal plant now converted to natural gas, and will be repurposing existing infrastructure to produce a new stream of fly ash sustainable for 70+ years.		
TRL: 8	**EMISSIONS REDUCTION POTENTIAL:** 10%	**LOCATION:** Transalta Power Plant
PROJECT VALUE: $48.7M	**ERA FUNDING:** $15M	**TIME TO FULL COMMERCIAL SCALE:** Entering commercial operations.
KEY BENEFITS: New alternative source of fly ash. Technology leadership opportunity to address a broader industry supply chain issue, while also reducing emissions and valorizing waste.	**KEY CHALLENGES:** Technology de-risking, forming new types of commercial partnerships between concrete and power sectors. Drying and purification of wet landfilled fly ash.	

FUTURE WORK OPPORTUNITY

Lafarge's reclamation facility at the Transalta power plant will de-risk the technology for Lafarge's global fleet. Once operating, the facility will produce CO_2 as part of its operations. In the future, there may be an opportunity for Carbon Upcycling Technologies to capture this CO_2 and utilize it to create SCMs (see Case Study #8).

CASE STUDY #8: CARBON UPCYCLING TECHNOLOGIES CO_2-ENHANCED FLY ASH			
OVERVIEW: Formed in response to ERA's Grand Challenge launched in 2013, Carbon Upcycling Technologies (CUT) utilizes CO_2 from flue gas and adsorbs it to nanomaterials, including fly ash. This creates a CO_2-enhanced SCM that results in enhanced concrete properties while also providing a carbon utilization pathway. This project will build on CUT's 3 tpd and 20 tpd pilots at the Alberta Carbon Conversion Technology Centre and support the first commercial-scale deployment of two new production facilities: a 50 tpd unit at the Burnco concrete mixing facility in Calgary, followed by a second stage 100 tpd facility with Lafarge at the Transalta reclamation site.			
TRL: 6-7	**EMISSIONS REDUCTION POTENTIAL:** 15%		**LOCATION:** Burnco in Calgary, Transalta reclamation site
PROJECT VALUE: $11M	**ERA FUNDING:** $4.4M		**TIME TO FULL COMMERCIAL SCALE:** <5 years.
KEY BENEFITS: Circular economy opportunity to valorize a waste material, reduce the amount of cement required in concrete, create a stronger, improved product, and permanently storing CO_2 flue gas in end-products (carbon utilization).		**KEY CHALLENGES:** Commercial acceptance of new concrete products and ability to prove durability. Technical challenges include cost and energy intensity, including access to a low carbon grid to fully reduce emissions.	

PARALLEL PATHWAY

CUT is expanding their technology to decarbonization of plastics and other materials. Through the Accelerating CCUS Technologies (ACT) consortium, CUT has a partnership with the U.S. DOE's National Renewable Energy Laboratory to test a variety of different feedstocks, trial different types of industrial wastes, and complete an overall market review. Additionally, CUT has a project in Ontario in which they are utilizing CO_2 captured from a cement plant and substituting clinker with their SCM.

5.4 CONSTRUCTION & CARBON UPTAKE

The following case studies demonstrate examples of decarbonization pathways for **construction & carbon uptake**, the final two pathways in the 5 C's.

CONSTRUCTION	The use of concrete products in the infrastructure around us.	**Techniques to reduce emissions:** **Design optimization** to limit overdesign without compromising safety and waste reduction on the job site to decrease hauling emissions and avoid contributions to landfills.
CARBON UPTAKE	An average of 20% of the CO_2 in the process emissions from clinker production can be permanently sequestered when a concrete structure is built, and surfaces are left exposed to the atmosphere.	**End of life concrete management**. With proper techniques, demolished concrete can sequester an additional 2% of process emissions. A further 1% is permanently sequestered if the demolished concrete is reused as an aggregate. **Recycling concrete** and enhancing the circular economy can avoid the need to obtain to extract new materials.

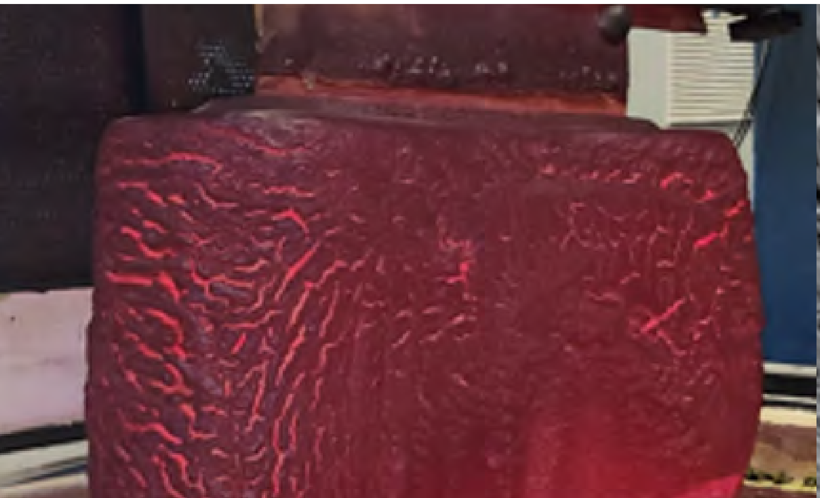
CASE STUDY #9: CARBON NANOTUBE-ENHANCED CONCRETE

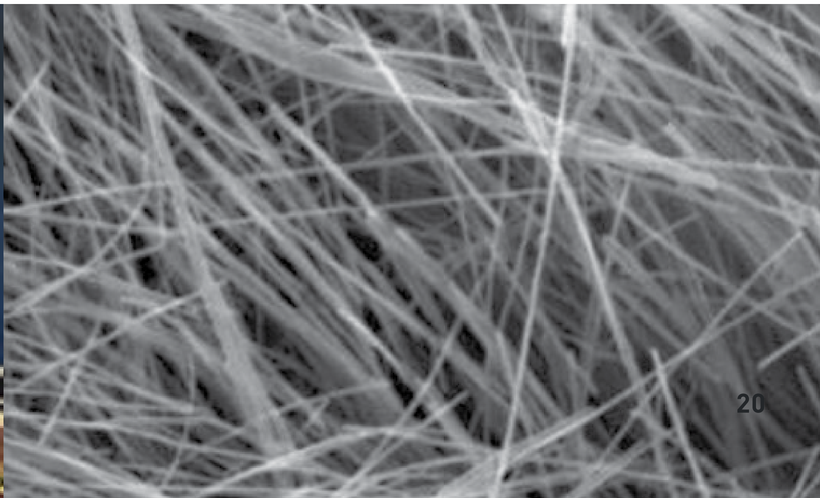
OVERVIEW: CarbonCorp has developed a technology called "C2CNT" (Carbon Dioxide 2 Carbon Nano Technology) that produces low-cost carbon nanotubes (CNTs) and oxygen (O_2) via molten electrolysis from captured CO_2. The resulting CNTs can be added to concrete on the order of ~0.05% by weight, resulting in up to a 45% strength increase, and thus reducing the total concrete required in construction. A commercial plant with a capacity of 2,500 tonnes of CNTs per year is being built at Capital Power's Genesee Generating Station (Genesee Carbon Conversion Centre (Phase 1), 2021) with support from ERA, targeting concrete and other markets, such as electric vehicles.

TRL: 7-8	**EMISSIONS REDUCTION POTENTIAL:** Enabled reductions up to 30%	**LOCATION:** CarbonCorp test facility in at the Alberta Carbon Conversion Technology Centre in Calgary
PROJECT VALUE: $14.3M	**ERA FUNDING**: $3M	**TIME TO FULL COMMERCIAL SCALE:** 5-10+ years.

KEY BENEFITS: Addition of a very small portion of CNTs acts as a kind of "nano-rebar" and enables up to a 45% strength increase compared to traditional concrete. Using Carbon Corp's technology, CNTs can be made in large quantities at low cost compared to other methods.

KEY CHALLENGES: Regulatory hurdles to introduce new substances take years to complete. Finding the optimal place to add CNTs to the concrete-mixing process without disrupting the manufacturing process is a key component to success. Perceptions that CNTs are high-cost, high-tech must be overcome. This is a promising mid-to-long opportunity for the concrete sector.





<table>
<tr><th colspan="3">CASE STUDY #10: CALGARY AGGREGATE RECYCLING REUSE OF DEMOLISHED CONCRETE & SOIL</th></tr>
<tr><td colspan="3">OVERVIEW: This project entails construction of a soil reuse facility co-located with current concrete recycling operations. The new facility is capable of recycling contaminated soil from construction & demolition activities. This will be first of its kind in Canada and third of its kind in North America. The facility washes contaminated soil and converts it into new aggregate products.</td></tr>
<tr><td>TRL: 9</td><td>EMISSIONS REDUCTION POTENTIAL: Enabled</td><td>LOCATION: Calgary Aggregate Recycling & Lafarge Exshaw</td></tr>
<tr><td>PROJECT VALUE: $20M</td><td>ERA FUNDING: $8.7M</td><td>TIME TO FULL COMMERCIAL SCALE: In commercial operation.</td></tr>
<tr><td colspan="2">KEY BENEFITS: Circular economy opportunity to valorize a waste material. Reduced emissions from transportation to landfill, reduced landfill waste, introduction of new products.</td><td>KEY CHALLENGES: Cost & de-risking of first of a kind implementation in Canada. Opportunities to enhance end of life concrete management.</td></tr>
</table>

FUTURE WORK OPPORTUNITY:

The contamination in the soil treated by Calgary Aggregate Recycling's facility is separated as clay, which Lafarge is trialling at their Exshaw facility as a raw material for cement. Lafarge is eventually targeting 30,000 tons per year for this material, or 1% of their raw mix, presenting a significant circular economy opportunity to augment their existing raw material supply.

5.5 TECHNOLOGY ROADMAP FOR THE CONCRETE SECTOR

Available today or in <1 year: Alternative kiln fuels, supplementary cementing materials, and improved end of life concrete management

Available in <5 years: Large-scale carbon capture, improvements to capture economics

Available in 5-10 years+: Next generation carbon capture technologies and process innovations, carbon utilization, and novel cement production

6.0 CONCLUSION

The ten case studies of innovation and collaboration in Alberta's concrete sector and associated work demonstrate the Canadian concrete industry's technology leadership and the impact of support through ERA and the TIER fund in scaling innovation. In combination with the recommendations noted by Concrete Zero and industry stakeholders, these and other technologies beyond the scope of this paper demonstrate a meaningful decarbonization pathway for 8% of the planet's emissions.

Concrete also has a unique, multi-faceted role to play in global decarbonization that it can tap into the entire value chain of CCUS as part of decarbonization and offers multiple pathways to circular economy solutions through valorization of waste. This creates the ability to forge new partnerships across diverse industries that wouldn't normally be expected to work together. Examples happening today include the Transalta power plant fly ash reclamation site and Lafarge's offtake of contaminated clay as a clinker feedstock from Calgary Aggregate Recycling.

Decarbonization requires both innovation supports and government action to enable commercial deployment. Continued collaboration between CAC, ERA and other stakeholders across the value chain can help de-risk implementation to achieve a net negative concrete industry in our lifetime, and offer lessons in leadership for other heavy industries worldwide.

Cement Association of Canada

EMISSIONS REDUCTION ALBERTA