Support of SB-596 Greenhouse Gases: Cement Sector Net-Zero Emissions Strategy

A Discussion of Ecocem ACT and High Filler Low Water Cements and Concrete in Context

By Steve Bryan, Managing Director of Ecocem Americas, 12-Jun-2023

A. Introduction and Objectives

This report presents critical considerations for the development of a comprehensive strategy for California's cement sector to achieve net-zero emissions of greenhouse gases associated with cement used within the state as soon as possible. It presents an overview of the key stages of the cement and concrete industry value chain and the opportunities to decarbonize each stage. It then reviews the California Nevada Cement Association publication, *Achieving Carbon Neutrality in the California Cement Industry, Key Barriers & Policy Solutions* (2021) in this context, followed by a similar review of the commercially available and emerging cement and concrete decarbonization technologies and practices, including Ecocem's ACT.

The second part of the report, Section D, addresses the market context and the most significant barrier to wide-spread adoption of the most promising decarbonization technology, High Filler, Low Water (HFLW) cement and concrete, the most advanced of which is Ecocem ACT, and suggests actions that could be taken to support widespread deployment to decarbonize California's cement and concrete industry as rapidly and as cost effectively as possible.

B. Executive Summary

The multiple industry cement and concrete decarbonization roadmaps, as well as those from NGOs and government, are cement centric and as a result are self-limiting. The scope of future strategies desperately needs to be expanded to include concrete, which offers tremendous potential to decrease the need for clinker and traditional cement. Cement is simply an ingredient in a complex assortment of products broadly referred to as concrete. When assessing decarbonization of the industry, failure to expand the system boundary to include the actual utilization of cement in concrete significantly limits the potential for the decarbonization and risks wasting time and resources on measures that never achieve the net-zero goal and could potentially be counterproductive. Evidence of this possibility is that the process and product technologies proposed in industry roadmaps to date fall far short of the net-zero goal, and as a result rely on government-subsidized emerging carbon capture utilization and storage (CCUS) technologies deployed in the long-term to deliver over 50% of the required industry decarbonization.

Given the magnitude of the CO_2 emissions from the cement industry and the anticipated global growth in concrete demand, both NGOs and governmental agencies have placed a high priority on decarbonizing the cement and concrete industry; and the marketplace has responded. There are an unprecedented number of emerging cement and concrete decarbonization technologies, with an unprecedented amount of private equity and government funding to support their development; however, to date, outside of a few entries, most of the proposed technologies lack scalability to produce industry-wide decarbonization. This is primarily due to their exclusive dependence on scarce raw materials and/or abundant low-cost renewable energy. Other popular technologies are not decarbonization technologies, but rather expensive storage options for a limited amount of commercial CO_2, both captured and manufactured.

By expanding the strategic scope to include concrete, including the largest concrete market segment, commercial ready-mixed concrete, it has been proven that concrete can be produced with significantly less clinker and lower portions of supplementary cementing materials (SCMs) by using engineered particle sized materials and specific chemical admixtures tailored to the constituent materials, i.e. HFLW cements and concrete, like Ecocem ACT. The required equipment capital cost, the process technologies and their operating costs are all on par with the current cement industry benchmarks. Clinker and SCMs can be replaced by limestone and other mineral fillers, enabled by a family of highly adaptable chemicals known in the industry as polycarboxylic ethers (PCEs), or superplasticizers. Together, these existing technologies can drastically reduce the embodied carbon in every cubic meter of concrete in the world and provide the "missing 50%" of cement industry decarbonization, dramatically reducing the need for technologies like CCUS. However, implementing these alternative technologies at scale will require a structural shift in the cement and concrete value chain. Such structural shifts in profitable billion-dollar industries are typically more difficult to implement than new technologies alone, and such a shift will likely require government intervention and/or deep-pocketed new entrants to overcome industry inertia and its inherent resistance to change.

Key Points:

- Successful strategies to reduce the greenhouse gas emissions from cement production will focus on ***the embodied carbon in concrete products as a primary metric for industry incentives***, e.g. the framework of the Marin County Low-Carbon Concrete
- Successful strategies will support, prioritize and incentivize technologies that do not produce CO_2 in the first place (Carbon Avoidance, CA) over long-term initiatives and more expensive technologies that facilitate CO2 production, capture, transport, utilization and sequestration (Smart Carbon Usage, SCU)
- Successful strategies will support the technologies with the most rapid and significant sector-wide emissions reductions, including those from new market entrants with alternative cement and concrete decarbonization technologies that can be implemented with, or without existing cement industry participation
- Priority should be given to the more near term and cost-effective cement and concrete decarbonization technologies, such technologies are the most likely to be adopted globally for maximum impact on climate change (See diagram in Appendix C)
- Priority should be given to the more scalable cement and concrete decarbonization technologies, specifically technologies applicable to both non-structural AND structural concrete production
- Incentives for embodied carbon in concrete products should account for the embodied carbon in commercially distributed CO_2, which can be captured or manufactured CO_2 , that is mixed and stored in concrete. Consideration should be given to lower cost alternatives to concrete for long-term sequestration and storage of CO_2 when available
- When government funds are allocated to accelerate development and deployment of decarbonization technologies for the cement and concrete sector, it should not exclude new entrants with alternative cement and concrete technologies

C. Overview of Decarbonization of the Cement and Concrete Industry

1. **Universal Pathway to Decarbonization.** Due to the immense global demand for concrete, and the fact that it's production traditionally requires very carbon intensive portland cement as its key ingredient, decarbonizing the production of cement is often noted as a huge opportunity for reducing global carbon emissions. However, portland cement is not an end-use product, rather it is an ingredient in the production of complex, varied family of products called concrete. Concrete is a material employed by architects and engineers to serve a variety of functions in society. While there are only a handful of portland cement product types around the world, there are tens of thousands of different concrete products, each tailored to provide different functionality in different environmental conditions. Any effort to decarbonize the cement and concrete industry must look beyond cement and contemplate the impact of any changes on the entire system of concrete production and use; both in terms of overall decarbonization and the quality of products and services provided by the cement and concrete industry.

   Breaking down the value change of the cement and concrete industry into its fundamental stages, it is possible to make a simple depiction of how it can be decarbonized. These stages are shown in Figure 1.

Figure 1. Five (5) Stages for Decarbonizing the Cement and Concrete Industry

   Decarbonization at each stage has a multiplicative impact on the decarbonization of the entire value chain; however, there are secondary impacts between the stages. It is essential to always consider the entire system to assess the overall impact of actions on decarbonization, and accordingly, when creating decarbonization metrics and incentives. In some circumstances actions that reduce carbon emissions in one stage could result in increased emissions in later stages or limit the opportunities for carbon reductions in later stages that could be implemented on a larger scale and/or more cost effectively.

Industry and Agency Roadmaps. Each stage of the path to decarbonizing the cement and concrete industry has different "levers" or "technology areas" with the potential to impact the embodied carbon in cement and concrete as presented in cement and concrete industry decarbonization "roadmaps". The primary levers are shown graphically in Figure 2 below the stage of the value chain they impact.

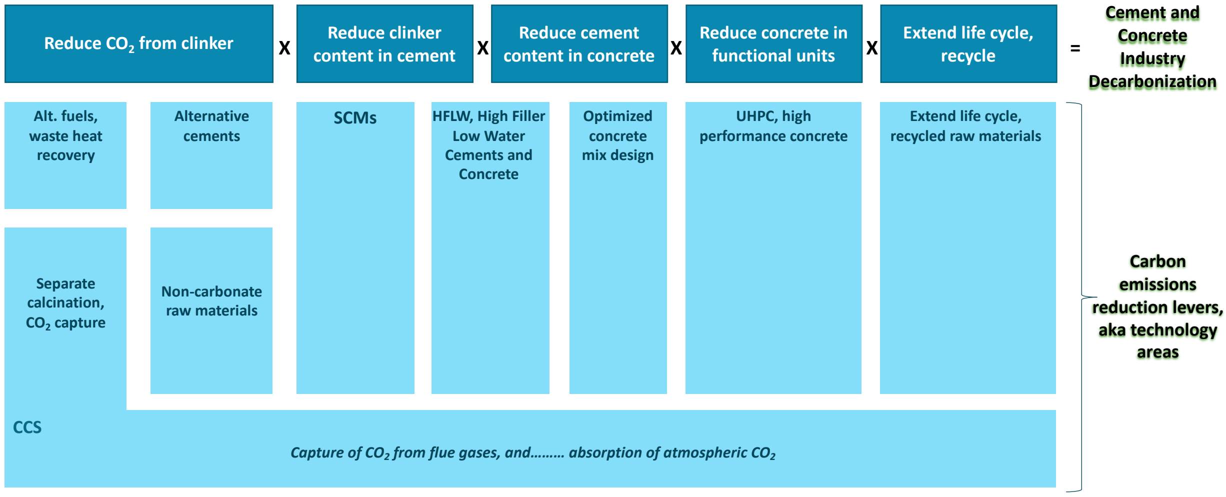
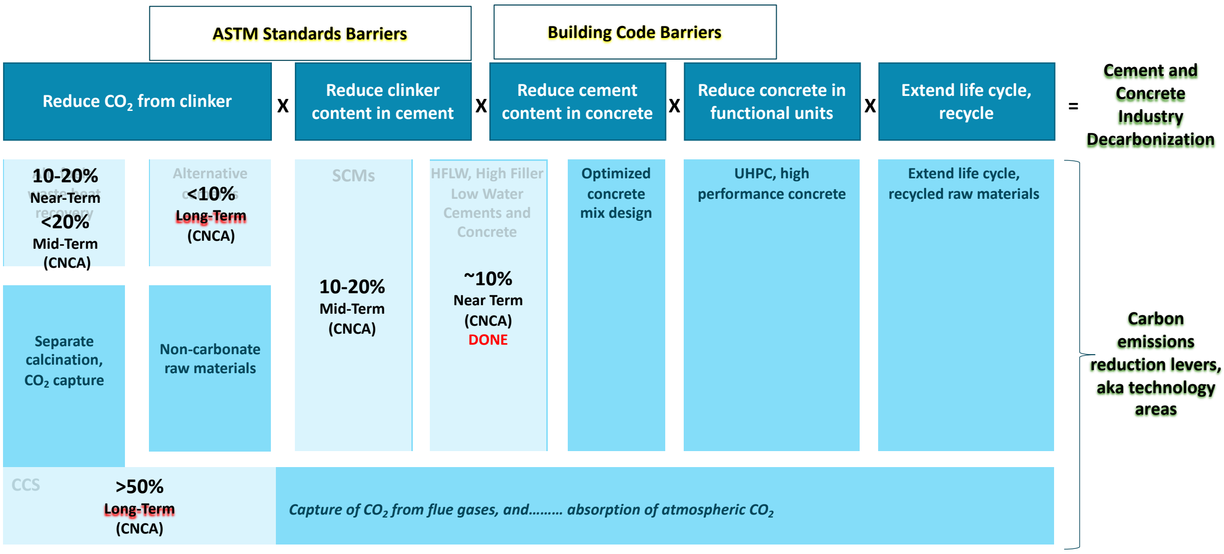


Figure 2. Carbon Emissions Reduction Levers, aka Technology Areas, for the Cement and Concrete Industry

Roadmaps, or equivalent, have been published by several different organizations, including the California Nevada Cement Association ("CNCA"), U.S. Portland Cement Association ("PCA"), Global Cement and Concrete Association ("GCCA"), ClimateWorks Foundation and the World Business Council for Sustainable Development (WBCSD)/ International Energy Agency (IEA). The roadmaps are all quite similar regarding suggested levers for decarbonization.

While recent publications and discussions lead by the U.S. Department of Energy and NGOs like ClimateWorks describe decarbonization of the cement ***and concrete*** industry, historically the industry decarbonization efforts and metrics have focused solely on cement, including language changes eliminating the word "concrete" in the development of the SB-596 legislation. This is a fundamental flaw when seeking to decarbonize the industry, as it addresses less than half the value chain, as shown in Figure 3.

The following discussion focuses on the CNCA publication, *Achieving Carbon Neutrality in the California Cement Industry, Key Barriers & Policy Solutions* (2021)[1]. The CNCA presented the decarbonization levers required to achieve 100% decarbonization of the California cement and concrete industry, shown figuratively in Figure 3, and described as follows.



CNCA - California-Nevada Cement Association's *Achieving Carbon Neutrality in the California Cement Industry* 38-Mar-2021

Figure 3. CNCA Cement Production GHG Reduction Levers, by Timing and Scale of Impact

a. **Portland Limestone Cement, 10% Near Term.** One near-term lever was Portland Limestone Cement ("PLC"), accounting for 10% of the journey to carbon neutrality. Implementation was very near-term. The industry and CalTrans were already in advanced validation testing at Oregon State University to support the use of ASTM C-595 Type IL blended cements with up to 15% limestone filler content (15% being 10% more than the 5% limestone filler already permitted with the CalTrans accepted cement, ASTM C-150 Type II/V). Most California cement companies were prepared to produce and sell the new PLC by the time the CNCA document was published in March 2021. This action was long overdue, California was reportedly the 44th of 50 state departments of transportation in the USA to accept the use of PLC. Countries in Europe and most parts of the world already allowed PLCs in one form or another

[1] https://cncement.org/attaining-carbon-neutrality

with up to 20% limestone filler since 1980s, and some current country standards allow up to 35% limestone filler[2].

Utilizing limestone directly in cement to replace portland cement clinker saves CO_2 from calcination, as well as the fuel and combustion product CO_2 from the kiln system to manufacture clinker, resulting in a significant savings in production costs, and an estimated $20-40 savings per ton of CO_2e eliminated for California cement plants. Typically, the limestone used in PLC cements is the same limestone that is mined and processed to create the raw material mixture that is reacted in the kiln system at cement plants, so it effectively bypasses the most energy and carbon intensive part of the cement manufacturing process. In addition, California cement producers can potentially make additional profit by selling surplus carbon allowances that result in California's Cap-and-Trade Program. This estimated cost savings to the cement producers, -$10 to -$40 is consistent with the global range published in a cost abatement curve by McKinsey in 2020[3] versus the estimated cost of CCUS $80-180/t.

b. **Alternative Raw Materials ("ARMs"), 10-20% Mid Term.** The CNCA cites a target of 70% clinker to cement ratio in California by 2045 through the addition of ARMs, aka Supplementary Cement Materials ("SCMs") when used in concrete, but the publication includes the caveat that the limited supply of alternative materials is a potential barrier to reaching this target, noting also that the industry is actively investing to increase the supply of ARMs, particularly natural pozzolans and calcined clays.

Note: this decarbonization lever is one that requires critical attention when setting industry metrics to measure and reward progress in decarbonizing the industry. If the use of ARMs by the cement industry for blended cements precludes or limits the use of the same or higher quality materials as SCMs at the point of concrete production, nothing is gained. In fact, it is quite possible that such market

[2] The European Union's harmonized standards for 27 common cement types, EN-197 Cement Part 1: Composition, specifications, and conformity criteria for common cements (2019)

[3] Laying the foundation for a zero-carbon cement industry | McKinsey https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement

conditions would result in higher CO_2 emissions in the California cement and concrete industry overall.

The most common ARMs, or SCMs, are fly ash and ground granulated blast furnace slag (“GGBFS”). As recently as 2019, California was using over 10% SCMs to substitute for cement in concrete plants. Nationally the number is over 10%, with some markets reaching 20%. Note that this is the same level of decarbonization targeted by the CNCA for ARMs, 10-20%. If that target is achieved by simply blending these ARMs/SCMs into cement and limiting or prohibiting their use directly in concrete, nothing is gained in terms of decarbonization. In either case, the limiting factor will be the availability of cost competitive ARMs/SCMs.

Interesting fact to note, a general “rule of thumb” in the industry is that 30% share, whether via ARMs in cement or SCMs in concrete, is the market saturation point; however, there are markets with extremely high concentrations of steel production per capita that exceed 30% market share due to the substantially higher substitution rates possible with GGBFS.

c. **Alternative Cements & Clinkers**, **<`10%, Long Term**. CNCA notes that the long-term performance of alternative cements and clinkers is currently unproven with a still uncertain range of emissions savings. That is not entirely true. Some well-established alternative cements are currently commercially available in the USA and around the world. These include alkali-activated cement (AAC) and a derivative called geopolymer cement, super-sulphated cement (SSC), calcium aluminate cement {CAC), calcium sulfoaluminate cement (CSA) and a variety of belitic cements just to name a few. All these cements have lower embodied carbon than ordinary portland cement, a fact that is easily quantified. Alternative cement technologies were the primary focus of decarbonization efforts of the cement industry and Silicon Valley green tech investors a decade ago with the likes of CalStar, Ceratech, Novacem, Vicat's (dba National Cement) Alpenat®, Heidelberg’s (dba Lehigh Cement) “BCT” and LafargeHolcim's Aether®. The principal reasons for these alternative cements not being more widely used in the industry is economic/commercial not technical. These low and ultra-low embodied carbon cements are commercially available for special niche applications; however, a scarcity of required raw materials, the historical lack of progress in developing ASTM cement standards as well as their incompatibility with current concrete industry materials and practices have limited their presence in the USA market. These limiting circumstances are not likely to change in the long-term, as the scarcity of suitable raw materials limits the scalability, and therefore limits the incentive to devote resources to develop new cement standards and convert industry infrastructure to accommodate alternative cement systems.

d. **Carbon Capture Utilization & Storage, >50% Long Term**: CNCA's publication states, "*carbon neutrality is out of reach for the cement industry in the absence of measures that would enable more aggressive deployment of CCUS*". The publication also notes that globally, the cement industry deployment of CCUS technology is still in the early stages with only a handful of projects in the pipeline, adding that major barriers to deployment remain, primarily in the form of high capital costs and significant project risk, as well as gaps in current incentives and a time-intensive permitting process. The publication cites cost estimates of installing carbon capture equipment at between $150 million to $360 million per cement plant, while the estimated costs per metric ton of CO_2 avoided range from roughly $50 to $100, depending on technology type.

e. **It is important to note that CCUS requires very significant quantities of electrical energy**, in most California cement plants CCUS could **double or triple the kWh per ton of cement production,** with no reduction in thermal energy consumption, and that's just for CO_2 capture. Additional energy and capital costs are required to enable CO_2 gas compression and transport in pipelines to the locations where the CO_2 can be stored long-term or utilized in a process that will sequester it long-term. It is often assumed in CCUS proposals that abundant low-cost renewable energy will be universally available; however, under that circumstance the threat from climate change will be effectively abated, and CO_2 from calcination for cement effectively rendered insignificant. On the other hand, if electricity costs rise significantly in the future due to scarcity of fossil fuel alternatives and high cost of renewable energy, the cost of cement production will be significantly impacted if it relies on CCS for decarbonization. The CNCA report concludes, with its conservative assumptions, in the absence of public funding and financing support, the California cement industry cannot afford to implement CCUS even with conservative cost estimates.

2. **Emerging Decarbonization Technologies and Companies.** Considerable resources have been dedicated to finding methods to decarbonize the cement and concrete industry. Most of that R&D effort and funding has come from outside the cement industry. There are numerous start-up companies proposing novel technologies, all looking for venture capital, government funding and cement industry investment to bring their technologies to fruition. A few of the well-publicized companies are shown in their respective technology or "lever" areas in Figure 4, and in a larger image at the end of this document.

   Describing each company and their various technologies is beyond the scope of this paper, but it is important to explain a couple of items.

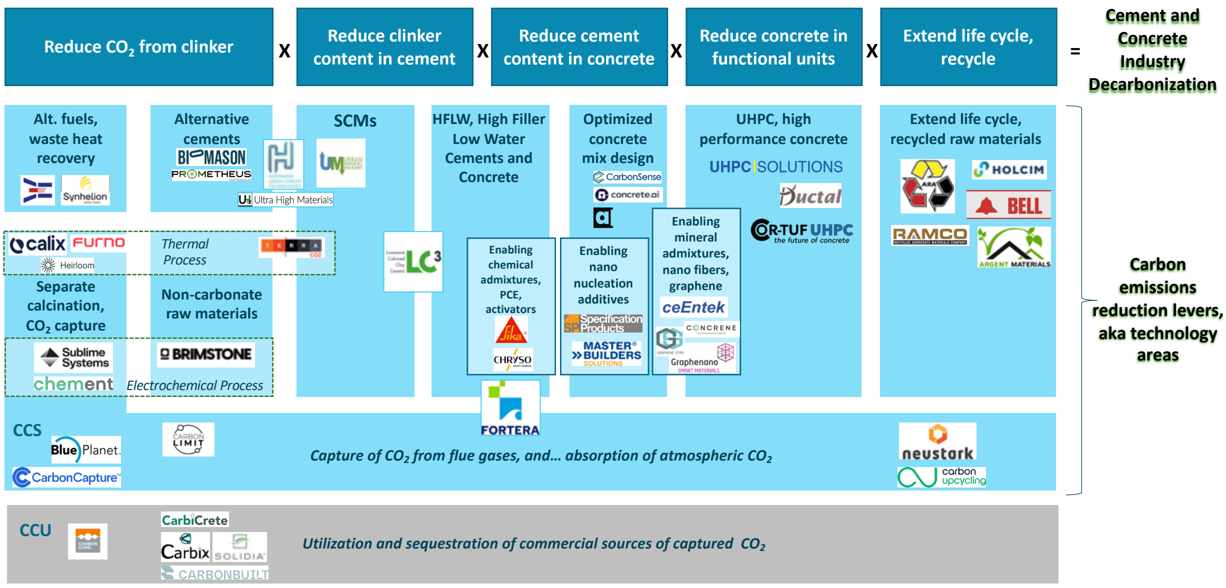


Figure 4. Cement and Concrete Industry Decarbonization Technology Companies

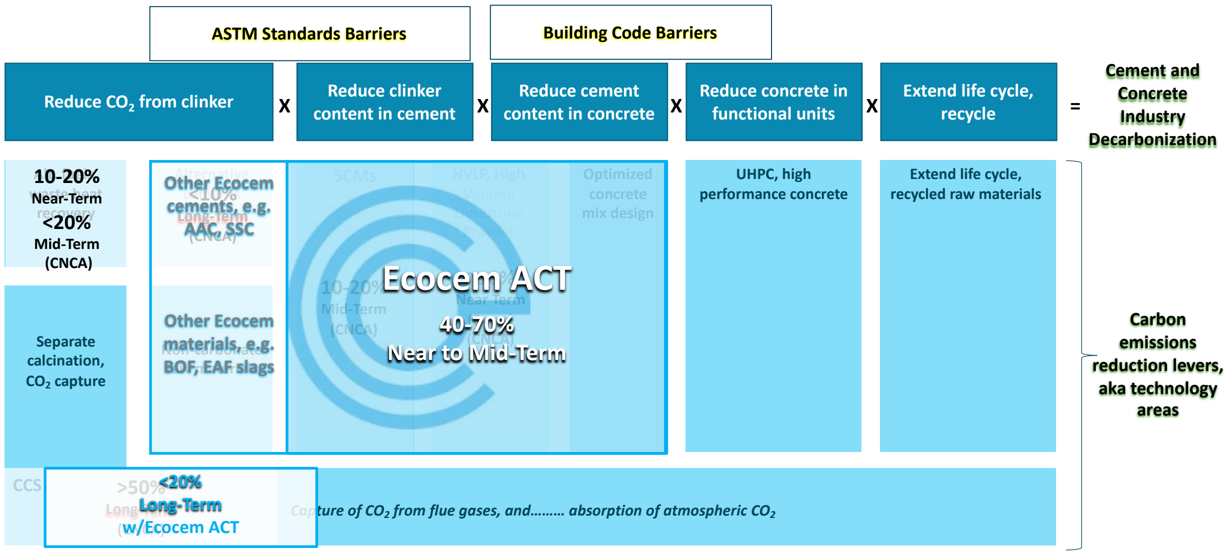


Figure 5. CNCA Cement Production GHG Reduction Levers, by Timing and Scale of Impact, as impacted by Ecocem ACT technology.

a. Enabling technologies. Figure 4 has added three additional boxes for "enabling technologies". There are several advanced technology companies providing products and technical support to the cement and concrete industry that facilitate decarbonization efforts. These include the major concrete chemical admixture companies, e.g. Chryso, GCP Applied Technologies, Sika and Master Solutions. Their products include special high range water reducers e.g., PCE superplasticizers, accelerators/activators, retarders, viscosity modifiers, strength enhancing fibers, nanofibers, graphene, as well as nano materials for nucleation to accelerate the concrete reactions. These are represented on the industry decarbonization levers diagram as overlays in their primary areas of use.

b. Carbon *Capture* Utilization and Storage Technologies. A few emerging decarbonization technology companies have technologies that capture CO_2 directly from power industry and cement/lime industry flue gases, e.g., CarbonCapture, Fortera, Blue Planet and Carbon Upcycling. These companies use compounds that mineralize the CO_2 gas to create materials for use as raw materials in the production of cement and/or concrete. This immediate transformation of flue gas CO2 to mineralized CO2 for long-term storage offers inherent logistical cost savings over simple carbon capture and transport solutions.

Some other emerging decarbonization technology companies add proprietary chemicals or minerals to absorb and sequester CO_2 from the atmosphere in concrete or recycled materials that are then used for concrete, e.g., CarbonLimit and Neustark.

Both these technological approaches are separate and unique from many of the others (described in the next section) because these technologies actually capture carbon that otherwise would be present in the atmosphere.

c. Carbon *Utilization* Technologies. Many companies, perhaps the largest single group of emerging technology companies for the cement and concrete industry, utilize technologies that ***do not capture CO_2*** during clinker production; instead, these technologies provide a means to store commercially available CO_2 long-term by using CO_2 as an ingredient in the production of concrete. These technologies typically use non-carbonate minerals and/or low-carbonate industrial byproducts in their cement formulations, and these materials react to effectively mineralize the CO_2. This is done in normal portland cement concrete in the case of CarbonCure; while other companies, e.g., Solidia, Carbicrete, CarbonBuilt, use CO_2 as an active ingredient in an alternative cement system to form carbonated calcium silicate compounds. In this case, these products are only suitable for non-structural concrete, like concrete masonry units (CMU) aka cinder blocks, pavestones, etc., which significantly limits the scalability of the technology to decarbonize the cement and concrete industry.

These are critical points of distinction. First and foremost, these technologies are not decarbonizing the cement and concrete industry since they do not capture carbon. The CO_2 they utilize has already been captured elsewhere, or co-manufactured during the industrial manufacture of ammonia, alcohol and fertilizers. The CO_2 is captured, purified and compressed in a multi-step process, and finally liquefied to be transported in pressurised tanks at a low temperature or compressed for transport in existing pipelines in some geographies. All of this process at considerable cost in capital investment and electrical energy, with additional energy used for further distribution, typically by truck to its point of use in concrete, often with the possibility for losses back to the atmosphere in these later steps. The use of commercially sourced CO_2 as an ingredient in concrete is simply another option for the long-term storage of captured CO_2 it is not decarbonization.

Many lower cost storage options for captured CO_2 gas are on the horizon. It is stated in several government reports that the saline strata in many regions on earth, including the USA, have multiple times the storage capacity required for captured CO_2 emissions. The storage of CO_2 in saline strata is above and beyond the beneficial use of injecting CO_2 into existing oil fields for "enhanced oil recovery" (EOR).

The use of CO_2 as an ingredient in ready mixed concrete and concrete product manufacturing has a cost, both commercially and environmentally. Arguably commercial CO_2 utilized in concrete should have an EPD developed to account for the embodied carbon of the electrical energy used for its capture, compression, and transport, as well as estimated losses in transit and in its use, to accurately compare its decarbonization impact for the cement and concrete industry versus the actual carbon capture utilization and storage technologies described in the prior paragraphs.

d. Electro-chemical production. Electro-chemical production of lime to facilitate CO_2 capture during calcination and to lower thermal energy requirements has been in development for over 15 years. One company, Calera, developed several patents (now held by its successor company, Fortera) and gained international recognition for its wet electrochemical approach to obtain calcium in solution for the generation of lime for cement production and/or for carbon capture in the form of precipitated calcium carbonate. Their product was proposed as a cement substitute during the 2008-2009 period. Calera has since closed, and its successor company, Fortera, has concluded that the electrochemical approach is not feasible, and has chosen not to pursue this pathway to decarbonization, despite their multiple patents in the area. Calera's founder, who is not a part of Fortera, has also chosen to not pursue electrochemical technologies for decarbonization. He has formed Blue Planet Systems to commercialize its own new technology for carbon capture and sequestration via mineralization of CO_2 in industrial flue gases as aggregate.

The use of electrochemical approach to produce lime relies on the availability of abundant renewable electrical energy, even more so than CCUS in existing cement plants. Electrical energy is used to effectively calcine limestone (e.g., Sublime, Chement) by itself to facilitate carbon capture, or to liberate calcium atoms from unique non-carbonate calcium bearing mineral deposits (e.g., Brimstone).

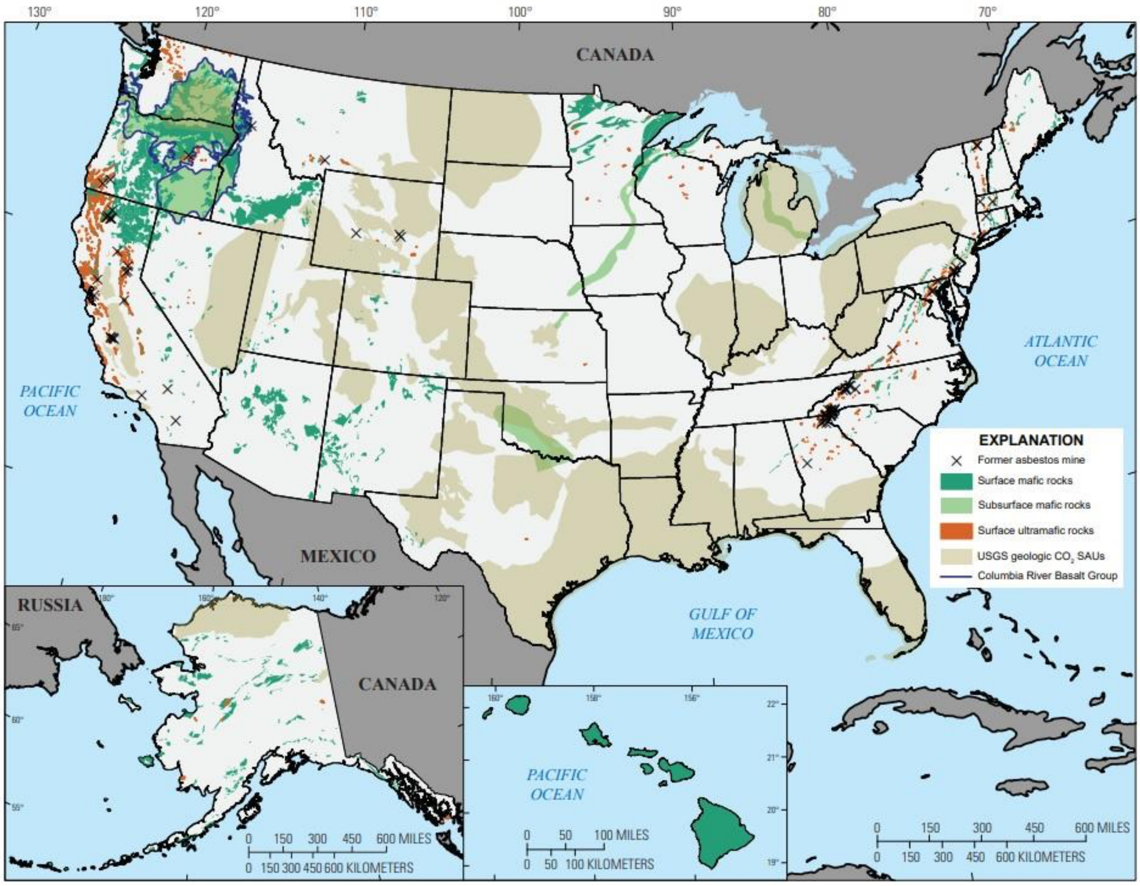


Figure 6. National map of mafic and ultramafic rocks in the United States[4] The surface rock, dark green and orange are the surface deposits of suitable rock for carbonation, or electrochemical calcium extraction. Other are suitable receptors for CO2 injection for in situ carbonization.

A map of suitable deposits of non-carbonate calcium bearing mineral deposits near the earth's surface for use in the second process are shown in **dark** green and orange in Figure 6. It is the best resource found to identify suitable raw materials for the Brimstone process. While the Brimstone website states that, "…calcium silicate is a

[4] Blondes, M.S., Merrill, M.D., Anderson, S.T., and DeVera, C.A., 2019, Carbon dioxide mineralization feasibility in the United States: U.S. Geological Survey Scientific Investigations Report 2018–5079, 29 p., https://doi.org/10.3133/sir20185079

hundred times more abundant than limestone” there are no reference cited and it has been difficult to locate these deposits geographically or geologically, or to quantify them. However, there are abundant references in literature stating that the most common calcium compound on Earth is calcium carbonate, (limestone). Furthermore, it is well known that calcium carbonate is a stable end-product from the natural rock weathering cycle of metamorphic calcium silicate rock that reaches the Earth surface or ground water; therefore, sedimentary calcium carbonate rock would be expected to be more commonly found at or near the earth’s surface versus calcium silicate rock.

Another consideration is calcium concentration in the rock and mining wastes. Limestone is calcium carbonate. In its purest form, limestone is 56% CaO, versus common calcium silicate rocks like basalt, which are around 10% CaO. Other calcium bearing silicate rocks, primarily mafic and ultramafic rocks, also contain much lower concentrations of calcium. Any processing of these rocks just for calcium for cement production will result in multiples of that volume of cement production in mining waste streams, creating a solid waste disposal issue. There are some rare calcium silicate minerals, such as wollastonite, with high calcium content (~48%), but they have a very high market value even as mined (circa $300 per ton), which is more than twice the current price of portland cement.

Another consideration is that these non-carbonate rock formations have been identified as potential repositories for long term sequestration and storage of captured CO_2. In this scenario, transport of captured CO_2 gas by pipeline to these remote unique mineral deposits and the injection of the CO_2 underground into the rock formations for long-term sequestration is likely to be a more cost effective decarbonization strategy versus mining, transporting and electrochemical processing the rock to produce cement. The production of cement in this fashion would require relocating current cement plants (transporting high volumes of this very low-calcium content rock to existing plants would simply not be feasible) and then transporting the clinker or cement products long distances to cement and concrete markets.

Finally, these rock resources are already contributing to decarbonization naturally, albeit on a very long-time scale. Basalt is the most common volcanic rock type on Earth, making up over 90% of all volcanic rock on the planet. Basalt outcrops weather relatively rapidly. Calcium released by basalts binds with atmospheric CO_2 to form calcium carbonate , acting as a CO_2 capture mechanism, without human intervention.

e. High Filler Low Water (HFLW) cements and concrete. The CNCA publication states, "*CCUS yields GHG abatement benefits on a scale otherwise not achievable by other measures.*" While CCUS is a potential long-term, high-cost decarbonization solution, GHG abatement benefits on the scale of CCUS for the cement and concrete industry are available, and on a far shorter time horizon, in the form of increased use of HFLW cements. Importantly HFLW technologies are Carbon Avoidance (CA) technologies, replacing high cost CCUS. HFLW cements can result in significantly higher substitution rates of limestone fillers at circa 50%, well beyond the typical 15-20% common in the industry today, resulting in a significant and immediate reduction in CO_2 emissions by 60-75% by significantly reducing the amount of clinker produced and its associated carbon footprint. Simple intergrinding of limestone has already provided the most significant and cost-effective decarbonization progress to date. Limestone fillers combined with SCMs are also making strides in the form of ternary cements, and the popular LC3. But the full potential is not realized without additional enhancements to the processing and concrete mix designs. Two fundamental technologies that are well developed. The use of HFLW cements and concrete is facilitated using engineered particle size distributions ("PSDs") to positively influence the rheological properties of concrete in the plastic state, i.e., "workability". The viability of the use of significantly increased portions of limestone fillers is supported by numerous researchers including a 2016 publication by researchers at the National Institute of Standards and Technology ("NIST")[5]. They note in that paper that "***with similar rheology (slump) and setting behaviors****, these high-volume limestone powder*

[5] Bentz, D. , Irassar, E. , Bucher, B. and Weiss, J. (2009), Limestone Fillers to Conserve Cement in Low w/cm Concretes: An Analysis Based on Powers Model, Concrete International, [online], https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=901137 (Accessed April 24, 2023)

("HVLP") mixtures could be substituted for current OPC formulations, with minimal adjustments by the concrete contractor anticipated".

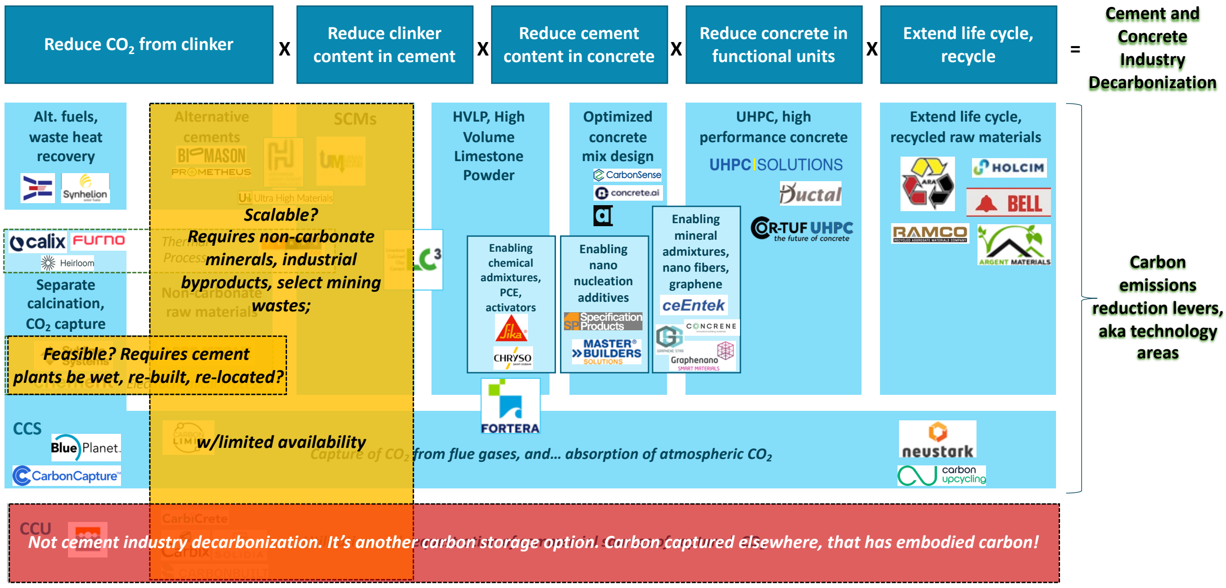


Figure 7. Cement and Concrete Industry Decarbonization Technology Companies, additional consideration

A second excellent technical publication provides an overview of the topic, "*Fillers in cementitious materials — Experience, recent advances and future potential*" by professors at the University of São Paulo[6] citing research publications around the world. This publication notes, *"…recent research developments show that it is possible to replace as much as 70% of clinker with filler without reducing mechanical strength. This can be achieved if dilution is compensated for by engineering a reduction in the amount of mixing water required to achieve the desirable rheological behavior. However, this is not a simple task because rheological behavior becomes increasingly difficult to control with reduced water content."* This is one of the critical areas addressed by Ecocem ACT's breakthrough technology.

A third document was published in May 2023 by the Department of Energy's Oak Ridge National Laboratory titled, *Low Carbon, High Filler, Low Water (HFLW) Concrete* by Denise Antunes da Silva, Senior R&D Staff Member; Nolan Hayes, Postdoctoral Research Associate[7]. In that brief summary of their research, they note, "*HFLW concrete reduces cement use by*

[6] Vanderley M. John, Bruno L. Damineli, Marco Quattrone, Rafael G. Pileggi, Fillers in cementitious materials — Experience, recent advances and future potential, Cement and Concrete Research, Volume 114, 2018, pp. 65-78, https://www.sciencedirect.com/science/article/pii/S0008884616311425

[7] https://www.energy.gov/sites/default/files/2023-05/bto-peer-2023-hflw-concrete-bemr-silva.pdf

>35% and concrete embodied carbon by >20% via higher packing density and rheological adequacy." And that future research is needed to *"…ensure robustness of HFLW concrete in ready-mix plants, or 90% of US concrete production, to overcome transportation challenge to workability (i.e., rheological behavior)"*. It is this research that Ecocem's Innovation team has done. Ecocem ACT is a solution to the critical "workability" issue, and at even higher filler substitution rates. Ecocem's discoveries will be presented in several papers accepted for the 16th International Congress on the Chemistry of Cement 2023 (18-22 September 2023) in Bangkok, Thailand.

Utilizing recent advances in chemical admixture technology, as well as developments and discoveries with respect to particle size distributions by Ecocem and others present the opportunity to extrapolate the gains of traditional ternary cements and LC3. Ecocem ACT requires an SCM at 20-30% in the cement, and this SCM can be GGBFS, calcined clay like LC3, natural pozzolan, fly ash, and potentially other byproducts and synthetic SCMs, e.g., TerraCO$_2$products. This aspect of Ecocem ACT is key to its scalability, it minimizes the quantity of SCM required, and opens the door to virtually any material with pozzolanic properties to be used as an SCM. (See diagram in Appendix D).

Ecocem ACT has been successfully demonstrated to achieve commercial rheological performance ("workability") in industrial scale ready-mixed concrete plants while also meeting commercial strength and long-term durability requirements. European Technical Approval permitting the sale of ACT cement throughout the EU is expected to be granted during the summer of 2023. Earlier, in May 2023, Ecocem and Cemex France announced a partnership for low-carbon concrete production in this fashion at ten (10) of Cemex's ready mixed concrete production plants in France, stating that if successful, the low carbon technology products will be rolled out across Europe and to other markets.

HFLW represent the most economically viable, scalable method to *significantly* decarbonize the cement and concrete industries in the short to medium term. Because it utilizes limestone as the clinker replacement, and limestone is the primary ingredient to produce portland cement clinker, the key raw material for clinker replacement is readily available to the industry. The required process technologies and equipment capital cost and their operating costs are all on par with the current industry benchmarks. These costs are a fraction of the additional costs required to proliferate the closet and best alternative, CCUS. Importantly, the use of HFLW cements do not necessarily require additional binder content within any cubic meter of concrete, meaning the decarbonization benefits at the cement level transfer directly to the concrete level through the resultant reduction in reactive binder in any volume of concrete.

D. Pathways to Widespread Deployment of Ecocem ACT

There are excellent papers addressing the many barriers to entry for new cement and concrete technologies. This has been a topic in the concrete industry for decades, well before the industry focus was on decarbonization. Perhaps the best paper is the most recent, "*Removing Barriers to Rapid Adoption of Carbon Reduction*", which was published in May by Principal Investigator Tom Van Dam, and composed by Larry Sutter, Doug Hooton, Sarah Lopez, and Al Innis for Breakthrough Energy. Rather than reiterate their points or attempt to paraphrase their conclusions on key points: risk tolerance, assignment of risk, the need for new ASTM material standards and their adoption by leading consumers such as state departments of transportation, a copy of their report will be provided with this report.

While all the barriers identified in the Van Dam report are significant, and must be addressed, there is an additional barrier to entry, specifically related to HFLW cements and concretes, that is perhaps the most inhibiting: the current industry structure requires transformation. This will be the primary barrier to widespread deployment of HFLW technology and is the primary reason the industry has not already evolved further in this direction, beyond the progress achieved by PLC and LC3, and the normal use of commercially available superplasticizers for HFLW concrete. ***Some industry sector, company or companies, must step up to add the grinding capacity for millions of tons of ultrafine limestone fillers, as well as storage capacity for intermediate products and blending capacity to produce these high performance ternary cements in order to facilitate wide spread deployment of Ecocem ACT and other advanced HFLW concrete technologies.***

1. **Background on Blended Cements**. The final stage of cement production is called "finish grinding" in the industry. In its simplest form ordinary portland cement is produced by grinding portland cement clinker (~95%) and gypsum (~5%) in finish mills. The typical

product has cement particles with a median size ("d50") of 10-15 microns, with virtually all the particles being smaller than 50 microns. The 44-micron fineness was established over time as being the industry standard where typically most of the clinker particles will be dissolved in water when mixing concrete and the clinker compounds formed in the cement kiln are made available to react with water and the dissolved gypsum and solidify around the fine and coarse aggregates to form concrete.

Over time adjustments to the basic cement formulation were made in most markets, whereby limestone and various locally available SCMs were also added to the finish mill feed in minor proportions to save money, extend production capacity and/or improve concrete durability with SCMs. In virtually all these circumstances the cement raw materials were milled together in the finish mills, a practice known as "intergrinding". By grinding multiple materials together in this manner, there is no control over the relative fineness to which each of the component materials are ground; and softer materials are ground finer than harder materials.

In time, under unique market circumstances e.g., parts of Germany and the Benelux, cement producers implemented the practice of separate grinding of constituent materials in order to achieve a specific fineness for each material and then blending the intermediate products together to produce a blended cement in order to optimize power consumption and product performance; however, the fineness of the clinker and constituent materials remained circa d50 of 10-15 microns, a fineness range for which the industry's installed mill and separator technologies were designed. While mill and separator technologies have evolved for improved energy efficiency, the nominal cement product finesses have crept only slightly higher for improved early strengths. For the most part cement product fineness, and the industry's approach to finish milling has remained roughly the same form for over one hundred years.

In most parts of the world a few cement companies dominate the cement and concrete industry. Concrete producers make do with the cements made available by cement industry. Globally, the predominant cements are blended cements that include minor portions of limestone and SCMs, leaving concrete producers only limited opportunities to significantly change concrete performance. However, in a few select markets, e.g., USA, Canada, UK, Australia, when SCMs became commercially available, cement producers hesitated to adopt the use of SCMs in cement or concrete, instead suggesting SCMs produced inferior concrete. Consequently, the concrete industry evolved with SCMs going directly to the concrete producers via independent marketers (e.g., in the UK Civil & Marine for GGBFS, in the USA, Koch Industries for GGBFS and Monex Resources for fly ash), rather than being used by cement producers in blended cements, as in Europe and Asia. This provided the concrete producers in those countries much greater control and flexibility in the production of a wide variety of concrete products.

2. **The HFLW Solution for Decarbonization**. While two component "binary" cements like PLC and three component "ternary" cements like LC3 use limestone fillers, the portion of limestone filler is limited to 20% or less. To significantly increase the amount of limestone filler and still achieve required concrete performance, the production of Ecocem ACT and other HFLW cements and concretes require the optimization of all inputs to cement and concrete production. It is not a simple matter of using "off the shelf" materials to produce Ecocem ACT concrete. Rather, the particle size distributions of each constituent material must be prescribed based on the materials reactivity, solubility, and rheological properties to achieve the required strength and durability in concrete. Once the cement formulation is optimized for strength and durability, there is a second optimization process to prescribe the superplasticizer molecule that produces the required workability in ready-mixed concrete operations. While this process is not simple, it can be made routine for a select set of raw materials and thus scalable and robust, but this process won't just happen by mere evolution of intergrinding ternary cements.

   Of particular importance is the finesses of the limestone powder. Portions of the limestone powder must be ground significantly finer than is possible on the installed finish mill capacity in the cement industry. Furthermore, this high fineness and ultrafine limestone must be produced at very high volumes, circa 50% of the required cement volume, equating to several million tons for the California market. While the capital investment for a greenfield ACT cement plant would be comparable or less than a conventional cement plant, retrofitting existing cement plants for full conversion to Ecocem ACT or other HFLW cements will require a significant investment in additional finish mill capacity to realize the full decarbonization potential[8] (it is anticipated the average cement plant may require $40-60 million in mill capacity, additional storage silos and blenders, although the actual cost will vary significantly plant to plant and market to market. Selection of the location(s) for blending the components to optimize transportation costs will be important. Another consideration is that a significant portion of the kiln capacity in the global cement industry will be made redundant in all but the most rapidly growing markets, e.g., India. The requirement for industry players to make capital investments (albeit at a fraction of the cost to implement CCUS) to decarbonize the industry using technologies of which they are not accustomed, and to produce products for which there is no current market (until such cements and concrete are approved by a major customer such as CalTrans) means that the most decarbonizing, most cost effective and most readily implemented decarbonization technology will not be deployed; unless a series of actions are under taken to provide very significant incentives for change. These incentives must be directed to multiple segments of the value chain, i.e. concrete producers as well as cement producers, to provide competition and financial incentives to all the industry players which must bear the risks and learning curve to adapt their practices to the new HFLW technology. And of course, before all that, the technology must be validated by the industry and accepted by CalTrans.

The required industry structural transformation is that effectively half the current cement consumption in California would be replaced by ultrafine limestone or other mineral fillers. While it can be assumed that the cement industry has the limestone reserves to produce HFLW cements (it will require less limestone than the equivalent clinker production), and it has the existing cement production and distribution infrastructure, it is possible that other players could be motivated to compete for this new segment of the cement market. Current aggregate operations, particularly those of companies that are vertically integrated through ready-mixed concrete would certainly be potential rivals, as would current GCC/PCC producers, e.g. OMYA, or even new market entrant(s). In the

[8] It is anticipated the average US cement plant would require $40-60 million capex for additional milling and blending capacity. However, because of the much lighter requirement for thermal energy, operational costs would remain in line with current, even with additional electrical grinding capacity required. This is in stark contrast to CCUS. Indeed, HFLW cements work in tandem with CCUS in that reducing the amount of CO_2 produced in the first instance significantly reduces the burden placed on CCUS.

current industry structure, these are the three major industry player groups that are best positioned to fill this gap in ultrafine limestone grinding capacity: cement producers, aggregate producers and ground calcium carbonate (GCC) producers.

Any or all these three industry player groups, or even other new entrants could step up to provide the high volumes of ultrafine limestone fillers required for widespread deployment of Ecocem ACT and other HFLW cements and concrete. Other factors that could impact which companies are first movers include the high degree of vertical integration in southern California, the high level of industry consolidation in the state, and the long and uncertain process of permitting new quarries and/or new grinding capacity in the State of California.

There is also the aspect of there being a "chicken and egg" scenario, since HVLF cements and concretes are not currently approved for use, there is no market, so no justification for investors and boards of directors to make the capital investment in ultrafine milling capacity. In addition, without the required superplasticizer technology in the hands of these same potential ultrafine limestone fillers producers, the market value of these ultrafine mineral fillers would be severely limited. The current market structure is unlikely to move beyond status quo, and evolve towards this revolutionary level of decarbonization unless there is outside stimulus by government or deep-pocketed new market entrant.

The outside stimulus by government could be two-fold:

1. A grant of circa $6-8 million for a demonstration project to validate HFLW technology in California, perhaps sponsored by the U.S. Department of Energy, the California Energy Commission, CalTrans or CARB.

   The demonstration project would involve the following stages:

   - Stage 1. Demonstrate that Ecocem ACT and other HFLW cements can be successfully formulated with a variety of local California OPC/PLC cements, SCMs (local pozzolans and GGBFS) and limestones that meet the ASTM C-1157 cement performance standard.

- Stage 2. Demonstrate that multiple different Stage 1 formulations using a variety of raw materials can be produced on a pilot scale (1 tph) mill system and blending plant using process technologies that are scalable to 1 million tons per year.

- Stage 3. Utilize the multiple formulations produced with the pilot facility in multiple ready mixed concrete plants, for different concrete applications to demonstrate performance on strength, durability, workability, and robustness of the Ecocem ACT technology according to ACI and CalTrans test methods and performance requirements.

- Stage 4. Produce a Product Performance Report assessing the potential for HFLW cements and concretes to meet the needs of the California market; and a Process Technology Report using data collected during Stage 2 to provide improved capital cost and operating cost estimates as well as data to produce the anticipated EPDs to quantify the reductions in embodied carbon in concrete under a variety of production scenarios to verify the decarbonization potential of the HFLW technologies in various California market areas, whether implemented by the cement industry, the aggregate/ready mixed concrete industry or others.

2. Support the development of guaranteed demand-side legislation and policies for the use of low-carbon concrete by State agencies, using embodied carbon in concretes as the guiding metric, including:
    a. Legislation and policies to incorporate cement and concrete into the State's Buy Clean California Act (BCCA)
    b. Legislation and policies that guarantee procurement of low-carbon cement and concrete, including ALL available supplementary cementitious materials (SCMs), for the MAJORITY of state agencies' requirements
    c. Low Carbon Product Standards for various concrete specifications and products

Appendix A - Additional comments specifically regarding SB-596

(1) Define a metric for greenhouse gas intensity and evaluate the data submitted by cement manufacturing plants to the state board for the 2019 calendar year and other relevant data about emissions of greenhouse gases for cement that was imported into the state to establish a baseline from which to measure greenhouse gas intensity reductions.

Cements produced in and imported into California must meet CalTrans and ASTM specifications, and therefore the embodied carbon per ton in imported products can be compared directly to the embodied carbon of domestic cements (kg CO2e per ton) of the same ASTM specification to determine border control adjustments.

California has always required a unique cement product versus standard globally traded cement quality standards. In the past the standard cement was an ASTM Type II/V, now it is an ASTM C-595 Type IL (15), aka PLC. Since a unique product is required, manufacturers (typically Asian cement producers) must convert full production lines to produce products meeting the California specification when orders are received by California importers. Historically California cement importers are the California cement producers; therefore, California cement producers select the quality requirements of imported cement. Quality parameters for imported cements are typically selected to be as close to the quality of the domestic production as possible to facilitate one for one substitution to optimize logistics and supply chain costs. This situation makes comparing embodied carbon contents of these very similar ASTM Type cements relatively easy.

(2) Assess the effectiveness of existing measures, identify any modifications to existing measures, and evaluate new measures to overcome the market, statutory, and regulatory barriers inhibiting achievement of the objectives described in this section.

The metrics to measure decarbonization of the cement and concrete industry must be in concrete, not cement. Cement is an ingredient, not the final product. And while historically using embodied carbon in cement as the metric to monitor decarbonization of the cement industry was practical, simple, and efficient; with the widespread adoption of EPDs, the tools are now available to use embodied carbon in concrete as the primary metrics. The metrics to evaluate both concrete performance and the embodied carbon in the concrete associated with that performance should be used as the measure of industry performance toward decarbonization.

Over emphasis on upstream metrics could be detrimental to progress, for example, low clinker factor cements that preclude the use of more reactive, lower embodied carbon SCMs in concrete could have a detrimental impact on potential sales volume of SCMs to the point that SCM providers exit the market or provide only minimal quantities to the California market. Some potential metrics are kg CO2e/ m3 concrete for each specific strength class, and/or kg CO2e/ (m3 * MPa) or their equivalent in Imperial units.

(3) Identify actions that reduce adverse air quality impacts and support economic and workforce development in communities neighboring cement plants.

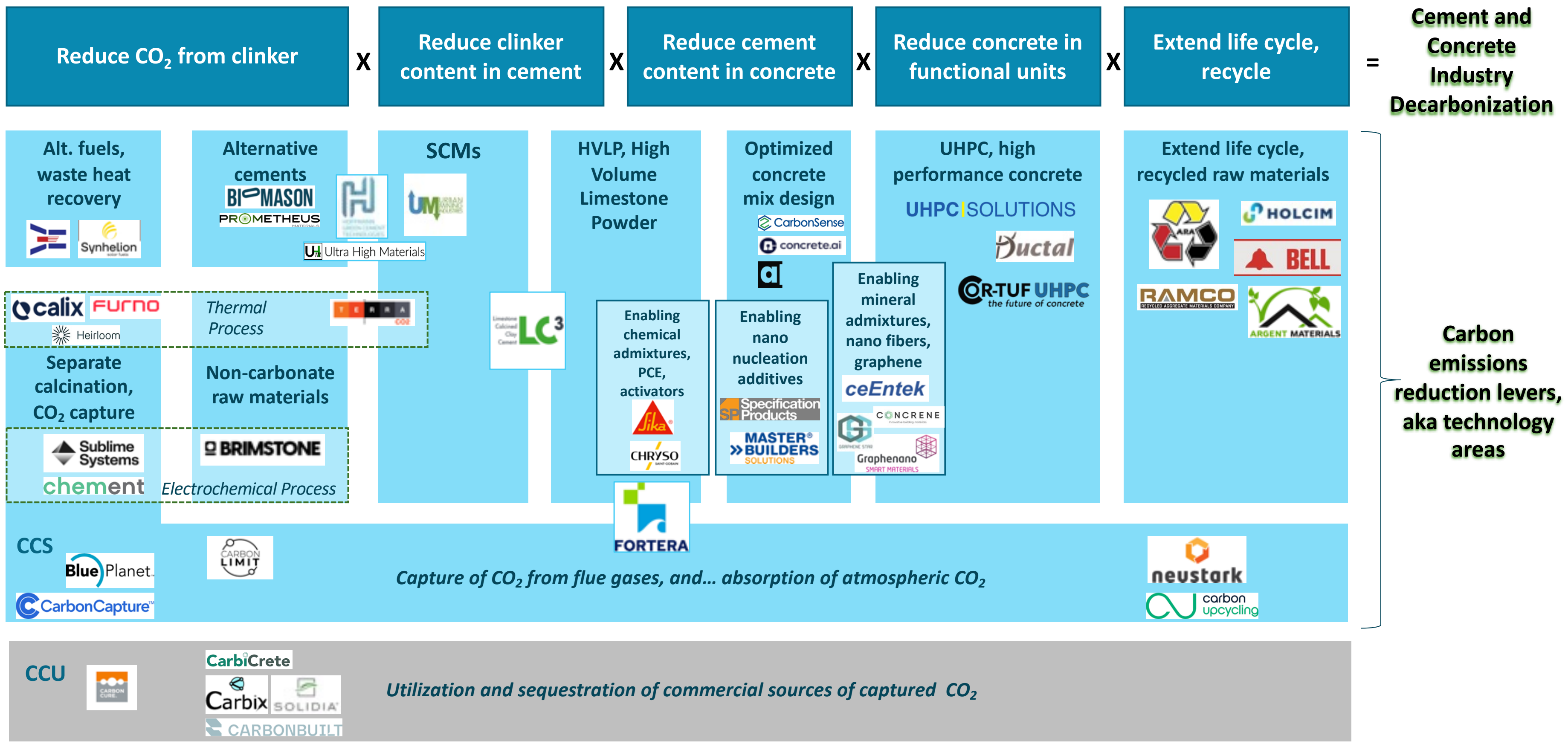
Lowering the amount of clinker required per unit of concrete by using high filler low water (HFLW) cements and concretes, like Ecocem ACT, will have a very significant positive impact on air quality that extends beyond CO_2 emissions. The kiln systems in California cement plants have been a major source of NO_X, SO_2 and mercury emissions. These emissions would be expected to drop by 40-70%, similar to the reductions in CO_2 emissions, but are very fuel and raw material dependent.

If the California industry adopts widespread production of HFLW cements and concretes, the powder consumption will remain the same and headcounts in operations to produce the powder, whether as blended ternary cements or SCMs and GCC would be similar for the industry, even if kilns are shutdown, overall, the quarry operations, milling operations, shipping and terminal operations will be maintained at the same throughputs.

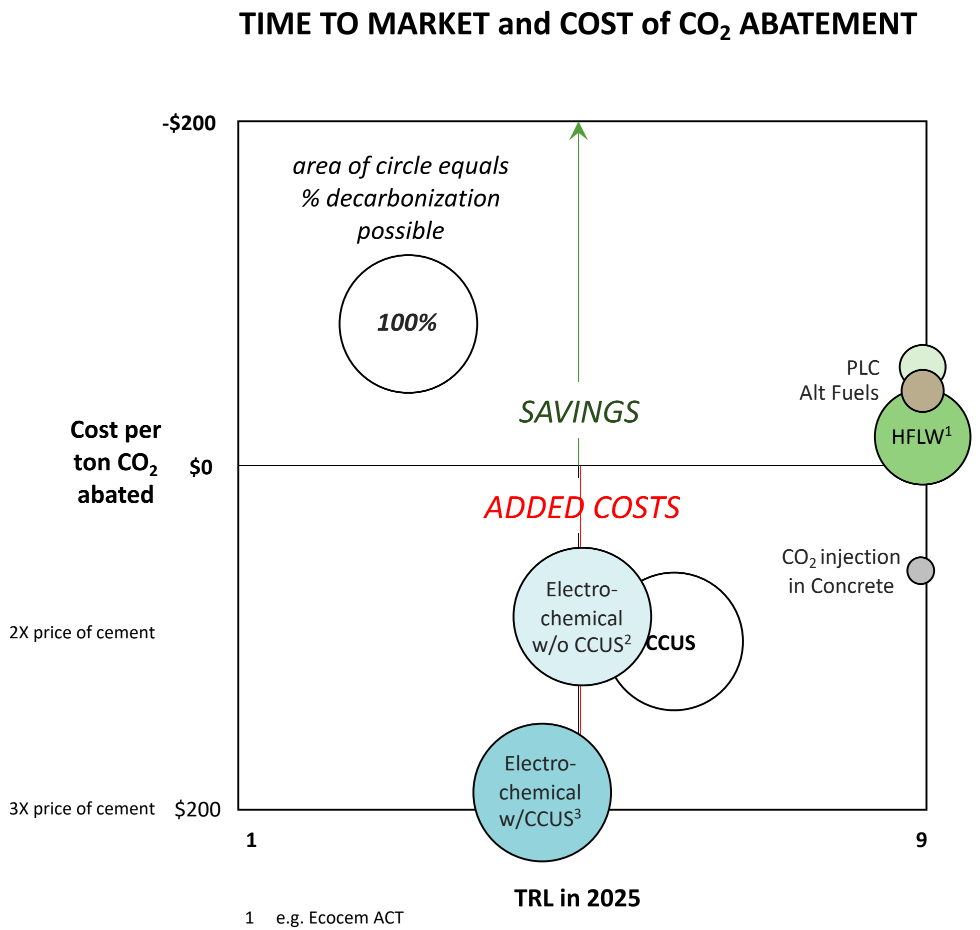
(6) Prioritize actions that leverage state and federal incentives, where applicable, to reduce costs of implementing greenhouse gas emissions reduction technologies and processes and to increase economic value for the state.

Sponsor the Ecocem ACT demonstration project. Focus metrics and incentives toward concrete, ala the Marin County Low-Carbon concrete directive. Support the legislation like SB-682 legislation but applied to the ***majority*** of the state's cement and concrete purchases but remove the language to eliminate fossil fuel based SCMs; these SCMs are industrial by-products with the lowest available embodied carbon, and are foreseen to be essential for CalTrans and other concrete purchasers to meet concrete durability requirements. Finally, pass green procurement legislation **for concrete**.

Appendix B Full Size Diagram of Cement and Concrete Industry Decarbonization Levers and Technology Companies

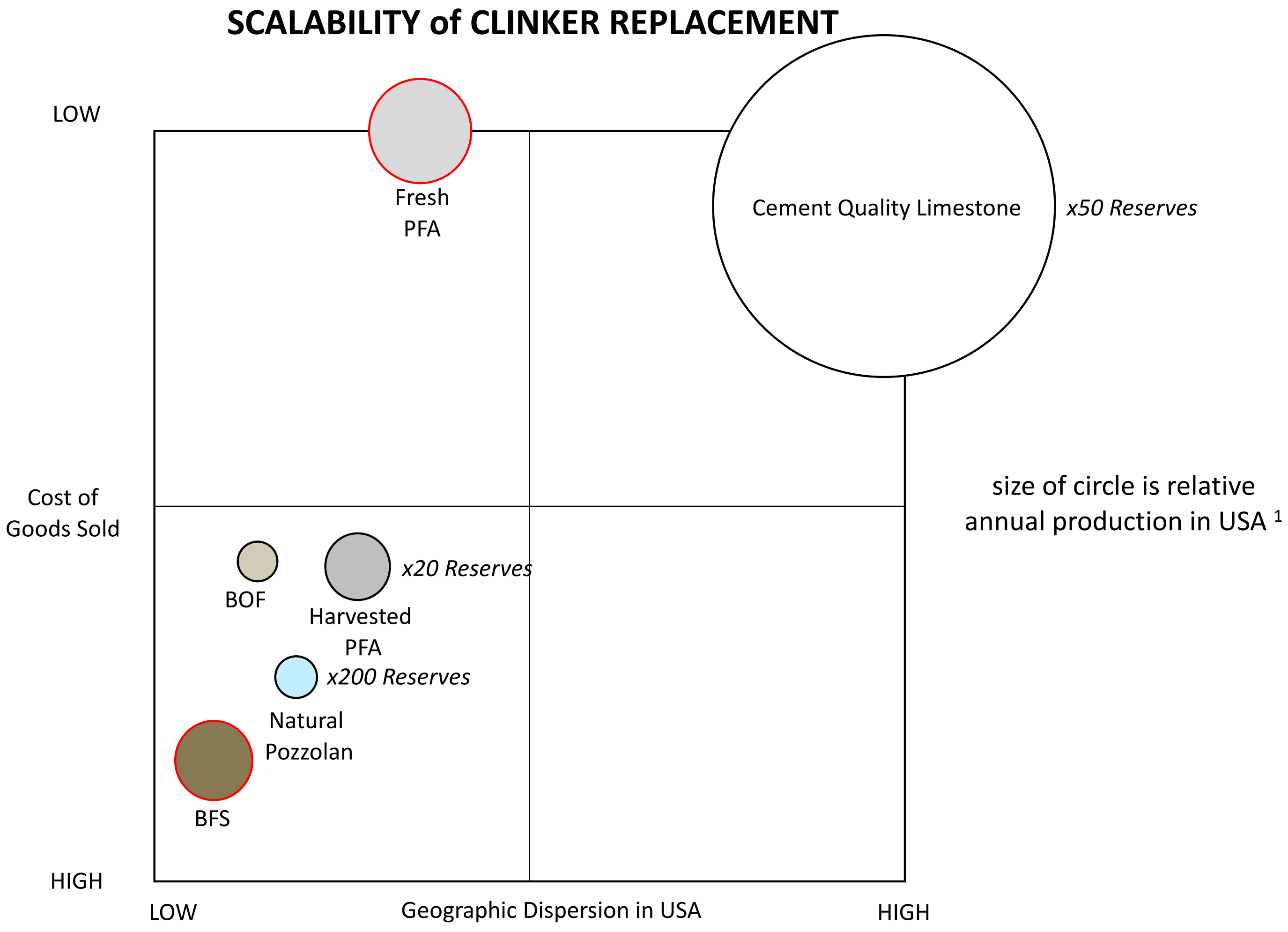


Appendix C Diagram of Estimates of Time to Market and Costs of Selected Cement and Concrete Industry Decarbonization Technologies



1 e.g. Ecocem ACT
2 e.g. Brimstone
3 e.g. Sublime, Chement

Appendix D Diagram of Estimates of Scalability of Various Clinker Substitutes



1 USGS, ACAA, WorldSteel, Ecocem estimates