January 2021

Sierra Club Guidance:
Cement Manufacturing

Sierra Club Cement Kiln Task Force

July 20, 2020

Executive Summary

The cement industry is environmentally destructive from cradle to grave. The most common type of cement is Portland cement, which is produced by converting limestone into the product known as “clinker” under the intense heat of a kiln, grinding the clinker to a fine powder, and then adding gypsum. Concrete is the construction material made by combining cement or other binder with filler material such as sand and gravel, and water. Cement (meaning Portland cement) manufacture depends upon extraction of nonrenewable resources, emits a host of air pollutants, and is the source of about 8% of the world’s carbon dioxide emissions. The industry has not sufficiently addressed global climate change. The Sierra Club supports a rapid and just transition in cement manufacturing to reduce its emissions. Cement kilns are large emitters of NOx, a smog precursor, which should be better controlled. Ammonia-based selective catalytic reduction (SCR), which reduces NOx significantly and does not impact CO2 emissions, should be widely deployed.

Nature-based solutions: Society can most readily address the damage caused by cement manufacture by replacing cement-based engineering with nature-based solutions.

Alternate Construction Material: There is no “one size fits all” best construction material to replace cement. Suitability depends on the type of project and on what materials are available, renewable, and affordable in a given region. Sufficient technical information about the raw materials, the impact on worker health and safety, manufacturing process, and product performance must be available for the public to be able to evaluate the product.

Alternative Cements: Precast applications for concrete, formed as bricks or slabs rather than poured on site, have made some headway in carbon reduction. Some estimate that precast cement could supplant up to 15% of the global cement market, which has the potential to cut back cement industry carbon emissions. Policies advancing technology-neutral, performance-based criteria for construction materials will advance the best-performing alternative cements.

Cement Plant Efficiency: Sierra Club support the adoption of excess heat recovery technologies by existing and new plants. The Sierra Club supports using efficient state of the art technology for new plants. The technology includes the use of dry process kilns (with minerals dry ground to a powder) having both a *preheater* (before the mix is fed into the kiln) and a *precalciner* (to increase the preheater’s efficiency). The inefficient wet process kilns (with minerals in a slurry) should be shuttered, and long-dry kiln operations updated or shuttered.

Fuel switching: All energy production based on combustion creates and aerosolizes pollutants, and releases carbon dioxide into the atmosphere. Only non-combustion energy resources have the potential to provide clean energy.

The Sierra Club opposes the combustion of municipal waste, hazardous waste, industrial waste, medical waste, solid waste - including petrochemical waste, waste tires, and other waste or fuel with non-biogenic components - for fuel, for treatment, and for disposal due to the emission of fossil carbon and hazardous air pollutants.

Biomass fuels are not clean fuels. They lack sufficient caloric value for the main firing of the cement kiln and are used as an adjunct to fossil fuels. The Sierra Club opposes relying on logging to produce biomass energy. Dedicated feedstocks that increase logging and displace wildlands can generate substantial carbon emissions and reduce existing carbon stores. Biomass fuels could reduce fossil carbon emissions where energy demands are low, and where it is affordable, sustainable, properly located and regulated, and reliably sourced.

Clinker substitution: The Sierra Club opposes substitution of cement clinker with fly ash, blast furnace slag, and other industrial waste products containing hazardous constituents. Monetizing the waste streams of intensive fossil fuel driven industries is counter to the Club's goal of eliminating waste generation and of reducing reliance on fossil fuel. In the U.S., the practice is to mix the clinker with the industrial waste at ready-mix cement plants rather than at the site of cement manufacture. The release of particulate pollutants from ready mix cement facilities into poor, working class, and minority neighborhoods is counter to the Club's goal of eliminating pollution releases into the environment, eliminating human exposure to pollutants, and advancing equity in environmental protection. Importation of fly ash and slag into the U.S. from overseas indicates that waste disposal, not carbon emissions reduction, is a driving force behind this brand of clinker substitution. Dependence on fossil fuel combustion by-products is a stumbling block, not a stepping stone, to decarbonization.

Ground limestone and natural pozzolans (materials with cementitious attributes) such as volcanic ash or calcined clay could also substitute for clinker. Emissions, however, must be controlled

Carbon capture: Carbon capture should only be considered in parallel with the most aggressive accepted decarbonization policy. At present, carbon capture for the cement industry has been examined in scattered pilot projects, but remains a pipe dream.

Alternative energy sources: Cement kilns have very specific heat requirements. At this time, the top three alternative energy sources to consider are biomass, resistive electricity, and hydrogen. Solar energy adapted to kilns is on the drawing board.

Policy recommendations: Innovation in the construction industry has not thrived. The industrial, political, and regulatory environment is largely hostile to environmental and community values. Policy changes are needed to spur innovation. To address contribution of the cement industry to global climate change, cement industry, the Sierra Club supports:

- the use of natural systems to accomplish building and engineering goals
- a just transition to decarbonization
- the transition of cement manufacturing from fossil fuel to renewable energy
- the adoption of sustainable low carbon building materials
- novel approaches to engineering, architecture, and building technology that reduce the use of cement while maintaining energy conservation of the built structures
- updating building codes and material specifications so that safe low-carbon alternative building designs and materials can compete in the market place

- government purchasing practices, tax codes, and economic policies that advantage sustainable low-carbon construction
- reducing the carbon footprint of cement manufacturing by the shutdown wet and long kilns; deployment of state-of-the art energy efficiency technology; use of non-fossil fuel derived, clean, renewable, sustainable fuels; banning of cement kilns for waste treatment and disposal; and use supplemental cementitious materials such as volcanic ash or calcined clay, with the understanding that continued dependence on by-products of fossil fuel combustion is a stumbling block, not a stepping stone, to decarbonization.

1 Introduction: The Global Carbon Cycle

Fossil carbon is naturally part of the slow carbon cycle that cycles globally, over geological time. Carbon is incorporated into geological formations (such as coal beds, limestone, and rocks) through sedimentation and metamorphosis. Eventually, carbon is slowly released into air, water, soil by rock weathering, volcanic action, and tectonic activity. Then, over eons, fossil carbon is reincorporated into geological formations by fossilization and rock formation.

Biogenic carbon is naturally part of the fast carbon cycle that cycles globally, in human time. Carbon is incorporated into organisms (like trees, fungi, and bacteria) from the environment through photosynthesis by plants or through chemosynthesis by some microbes. Eventually, after passing through the food chain, carbon is released into the atmosphere, the ocean, and the soil by metabolic processes and decay. Then the carbon is reincorporated into growing organisms, moving again from the environment to the food chain.

The balance between the slow carbon cycle and the fast carbon cycle has, in human time, maintained a steady global cycling of carbon between the biological, geological, and environmental components. Now, fossil carbon is being released rapidly from geological reservoirs (from coal beds, oil deposits, limestone, and shale), by human action, in human time rather than in geological time, and it cannot rapidly recycle back into the geological reservoirs. As humans have subjected geological reservoirs to burning and industrial processing, fossil carbon has accumulated in the atmosphere.

Changes in the global carbon cycle resulting from the release of fossil carbon into the atmosphere shifts carbon out of one reservoir and puts more carbon into other reservoirs, disrupting the balance of the cycle (Figure 1). Accumulation of fossil carbon in the atmosphere has led to climate change; accumulation in the oceans has led to acidification; and accumulation in soils has led to alteration of soil properties and processes. Moreover, accumulation of fossil carbon in the atmosphere has disrupted life on earth as organisms contend with climate change, ocean acidification, and soil alteration. Depletion of biogenic carbon by deforestation, clear cutting and soil disruption (Bormann et al. 1968) has further accelerated the accumulation of biogenic carbon in the atmosphere. To arrest global climate change and the accompanying damages, we must enable the repair of the global carbon cycle by ending releases of fossil carbon by combustion and industrial processing of geological deposits, by restoring forests and soil health, and by intervening to arrest species extinction wherever possible.

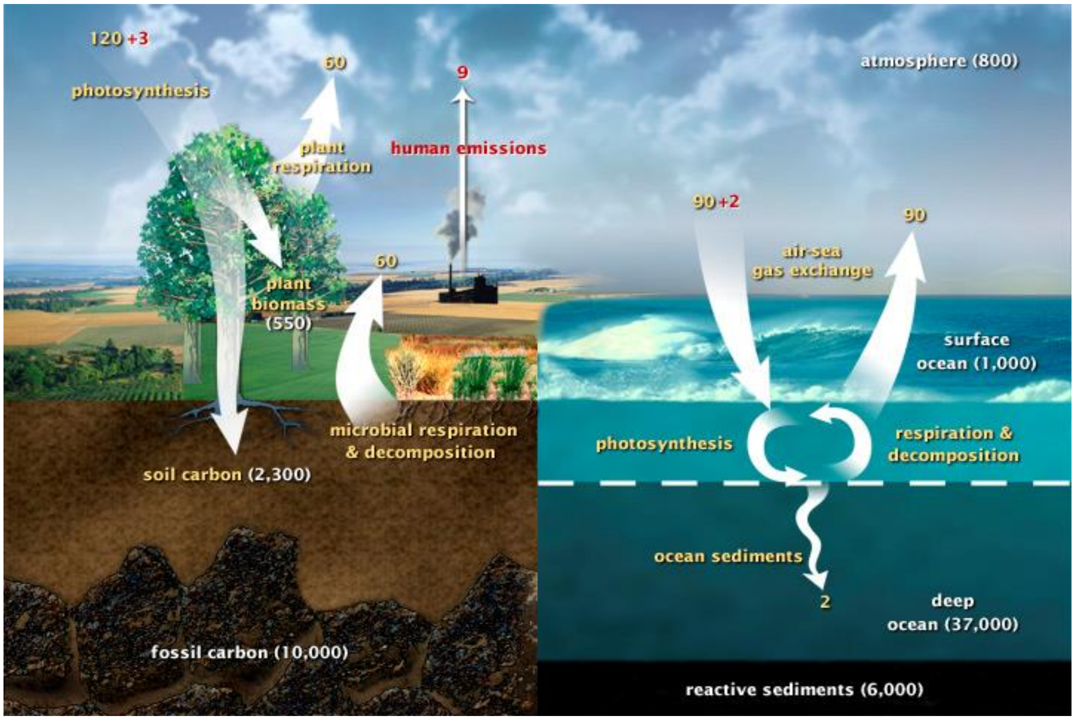

Figure 1. Fossil carbon entering the atmosphere as human emissions and impacting the global carbon cycle. Yellow numbers are natural fluxes, and red are human contributions in gigatons of carbon per year. White numbers indicate stored carbon. (Source: Adapted by NASA's Earth Observatory website from U.S. DOE, Biological and Environmental Research Information System.)

2 Climate, Coal-fired Power Plants, and Cement Manufacturing Facilities

The Sierra Club opposes coal-fired power plants due to the environmental damage that occurs with coal extraction; the release of *fossil carbon* and the pollution of air, water, land, the food chain, and local communities when fossil fuel is burned; and the environmental damage caused by disposal of mine tailings and the combustion residue fly ash (Energy Resources Policy).

Cement manufacturing also contributes fossil carbon emissions. Portland cement, the most common type of cement worldwide, is produced by chemically transforming limestone to the product known as "clinker" under the intense heat of a kiln, grinding it to a fine powder, and then adding gypsum. Concrete is the construction material made by combining cement or some other binder, with filler material such as sand and gravel, and water. Cement (meaning Portland cement) manufacturing facilities use electricity generated by coal-fired power plants. In addition, the cement manufacture emits fossil carbon as fossil fuel is burned to directly generate energy for manufacturing and to process the carbon-rich raw material limestone, which releases fossil carbon as it is transformed by heat energy into the makings of cement.

World-wide in 2010 (Fischedick 2014):

- *indirect electricity and heat production* (such as coal-fired power plants) emitted 5.25 $GtCO_2eq$

- *direct energy production* (such as coal and coke burning to heat cement kilns) emitted 5.27 $GtCO_2Eq$
- *process emissions* [such as CO_2 emitted by limestone calcination] emitted 2.59 $GtCO_2eq$

Therefore, based upon the Sierra Club's commitment to protect and restore the quality of the natural and human environment (Sierra Club Mission Statement), the Sierra Club supports a rapid and just transition in cement manufacturing to reduce its indirect electricity and heat production, its direct energy production, and its process emissions.

2.1 Cement and Climate Change: Tinkering, Transition, and Transformation

The approach to remedying ongoing environmental damage requires some *environmental tinkering* such as changes to our personal behaviors such as turning off lights, some *environmental transition* such as improved industrial processes and efficiency, and some *environmental transformation* such adopting nature-based solutions over engineering projects, replacing non-renewable energy sources with renewable energy sources, and replacing energy intensive products with environmentally-friendly products. All of these approaches – the tinkering, the transition, and the transformation - will be necessary to address the problem of cement manufacturing.

2.1.1 Why Transformation is Job One

Sierra Club's overall energy resources strategy (SC Energy Resources Policy) aims for the reduction all forms of pollution, not just greenhouse gases, and promotes species protection, environmental justice, and security. The cement industry is environmentally destructive from cradle to grave. Cement manufacturing is an energy-intensive process that grinds and heats the mixture of raw materials - limestone, clay, sand, and iron ore - in a rotary kiln to produce clinker, which is a grey nodular material. The clinker is cooled, ground to the consistency of facial powder, and then mixed with a small amount of gypsum to produce cement. Concrete (confusingly also often called "cement") is the mixture of the "binder", which is usually the Portland cement being discussed here; the "filler", which is material such as sand, gravel, and stone; and water to form a construction material.

Cement manufacture depends upon extraction of nonrenewable resources including coal, limestone, and sand. Cement production releases air pollutants from:

- the grinding and milling raw materials
- the fossil fuel burned to fire the kiln
- waste incinerated for disposal in the kiln
- process emissions from the chemical transformation of limestone
- cement kiln dust (the industrial waste product) transport and management
- the grinding, cooling and material handling of the clinker and other materials used to create concrete

Air pollutants of concern that are emitted by cement plants are *criteria air pollutants* (carbon monoxide, lead, nitrogen dioxide, ozone, particulate matter, and sulfur dioxide), *volatile organic compounds*, and a host of *hazardous air pollutants*, predominantly mercury, hydrochloric acid (HCl), benzene, dioxins and furans (polychlorinated dibenzodioxins and polychlorinated dibenzofurans), and, depending on the raw materials, metals such as lead and hexavalent chrome. Cement kilns are large emitters of nitrogen oxides (NOx), a smog precursor, which should be better controlled. Ammonia-based selective catalytic reduction (SCR), which reduces NOx significantly and does not impact CO_2 emissions, should be widely deployed. (Although the SCR based on a urea reaction has raised concerns because it releases CO_2, the SCR based on either an anhydrous or aqueous ammonia reaction does not release carbon.) Some of these air pollutants are the constituents of soot and smog, some are carcinogens, and all damage human health in various ways. Taken together, these pollutants cause systemic damage to the human body, variously damaging the human body's organ systems including the respiratory, cardiovascular, immune, nervous, endocrine, reproductive, excretory, digestive, and integumentary (skin, hair, nails) systems. In addition, these pollutants damage wildlife populations, habitat, livestock, and property, such as buildings and monuments. The other air pollutant of concern is carbon dioxide, CO_2. Carbon dioxide has caused systemic damage to the planet itself.

The cement industry is not keeping up the pace needed to prevent global climate damage. Cement production is the source of about 8% of the world's carbon dioxide emissions (Lehne and Preston 2018). In the cement kiln, the fossil fuel burned to generate intense heat releases large amounts of fossil carbon. Compounding the injury, the chemical transformation within the kiln of the raw material limestone to the lime used in cement production *releases fossil carbon from the limestone itself*, even more than is generated by the fossil fuel combustion. The intense heat and specific heating conditions required to produce clinker do not lend themselves easily to clean energy sources, and limestone is the main ingredient of cement, so cement manufacture has remained a major source of fossil carbon emissions.

Is the cement industry poised to slash their carbon emissions? No. The Sierra Club supports a target of less than 1.0°C of climate warming in 2100 (Sierra Club 2020 [Climate Resilience, Carbon Dioxide Removal, and Geoengineering Policy]), but other sources target a lax and less protective 2 °C climate warming cap. The 2018 CDP (formerly the Carbon Disclosure Project) report (Kisic et al. 2018) examined the performance of 13 of the largest publicly-listed cement companies globally. The report summarizes the situation as "The universe of [cement] companies has on average reduced their emissions intensity by 1% [per annum] over the last 4 years but this is not enough for a 2-degrees trajectory and would need to more than double to meet a 2-degrees target." So, even measured against a lax standard, the cement industry is falling woefully short of limiting its contribution to climate change.

How has Sierra Club addressed the ongoing damage being done by the cement industry? Existing Sierra Club conservation policy (https://www.sierraclub.org/policy) and a multitude of legal actions have expressed and implemented the Club's position on the cement industry's emissions of hazardous air pollutants and criteria air pollutants, and on the disposal of the kiln waste product cement kiln dust. We have opposed the incineration of non-biogenic wastes in cement kilns for the purposes of energy recovery, waste treatment, and waste disposal, because they emit hazardous air pollutants. Our actions over the last three decades have placed constraints on the cement industry, but have not remedied the ongoing global environmental damage by the industry.

2.1.2 What Transformation Looks Like

Transformation means moving beyond cement as a construction material. First, we must abandon the manifest destiny of construction that dictates that engineering solutions are how to get things done, nature is something that must be defeated, and cement is the means to those ends. The new paradigm supported by the Sierra Club is to prioritize nature-based solutions, including rejecting damaging cement-based projects. Second, we must adopt the use of renewable construction materials.

Transformation: Nature-based solutions

Nature-based solutions is the first track to transformation. In the case of cement, its final uses are all too often ill-conceived and costly. For example, flooding could be diminished by decreasing impermeable land coverings, restoring riparian ecosystems, and restoring wetlands. Dam failure has devastated downstream communities and caused catastrophic financial losses for investors. There has been "grievous harm done to people displaced by dams, a number now much greater than the 40 to 80 million people conservatively estimated by the World Commission on Dams in 2000, and the damage dealt to a majority of the world's river systems and fisheries, enough to cut into the livelihoods of another half-billion people living downstream from dams" (Leslie 2018). In addition to dam building, there is road building, highway expansion, building construction, and infrastructure expansion. So, we must also consider that "…the most severe, but least understood, impact of concrete…is that it destroys natural infrastructure without replacing the ecological functions that humanity depends on for fertilisation, pollination, flood control, oxygen production and water purification…" (Watts 2019). The Sierra Club favors measures that do no further environmental harm, repair damage already done, and protect biodiversity. Such approaches provide multiple co-benefits to human and natural communities, and are often comparatively cost-efficient and long-lasting (Sierra Club Climate Resilience, Carbon Dioxide Removal, and Geoengineering Policy).

Transformation: Innovation in Construction

Innovation in the construction industry has not thrived. The industrial, political, and regulatory environment is sensitive to economic considerations, but largely hostile to environmental and community values. The unfettered operation of and support for carbon intensive industry has failed to leave an adequate opening for innovative approaches and technologies. Dated and narrow material specifications and building codes choke out low-carbon building materials and construction approaches. Resources like economic support, government contracts and tax codes go to entrenched interests. Survival in the marketplace is stymied because architects, engineers, and customers flock to the familiar carbon-intensive designs, engineering practices, building materials, and purchases. Innovation withers. While we can review the pros and cons of various materials here, it is not the failure of these seeds of innovation to germinate; it is the hostile ground where all the already-thriving weeds benefit, and new growth is choked out. Later, we will review some policy steps to prepare the soil that will encourage transformation to a low carbon society.

Transformation: Alternative Construction Materials

Developing and adopting renewable and reliable alternative construction materials is the second track for transformation. Currently, "Most Portland cement is used to make concrete, mortars, or stuccos, and competes in the construction sector with concrete substitutes, such as aluminum, asphalt, clay brick, fiberglass, glass, gypsum (plaster), steel, stone, and wood" (USGS 2020). These materials are available now and, depending on the application, some of these competitors could result in a lower carbon footprint.

The vast potential for alternative binders for concrete (alternative to Portland cement in the concrete mix) (ABCs) and alternative sustainable construction materials was laid out in Figure 2 at the 2017 Alternative Materials in Sustainable Construction international conference. This list has not been curated by the Sierra Club and it is possible that some materials would never be suitable due to environmental impacts. Some alternatives, such as cross-laminated timber (layers of dried lumber boards glued together in alternating directions), have been considered by the Sierra Club and found to be problematic due to the impact of logging on forests and forest carbon (see Sierra Club's "Forest Carbon, Protection and Stewardship"). There is no "one size fits all" best construction material. Suitability depends on considerations such as the type of project, what materials are available in a given region, what materials are renewable in a given region, and what materials are affordable in a given region.

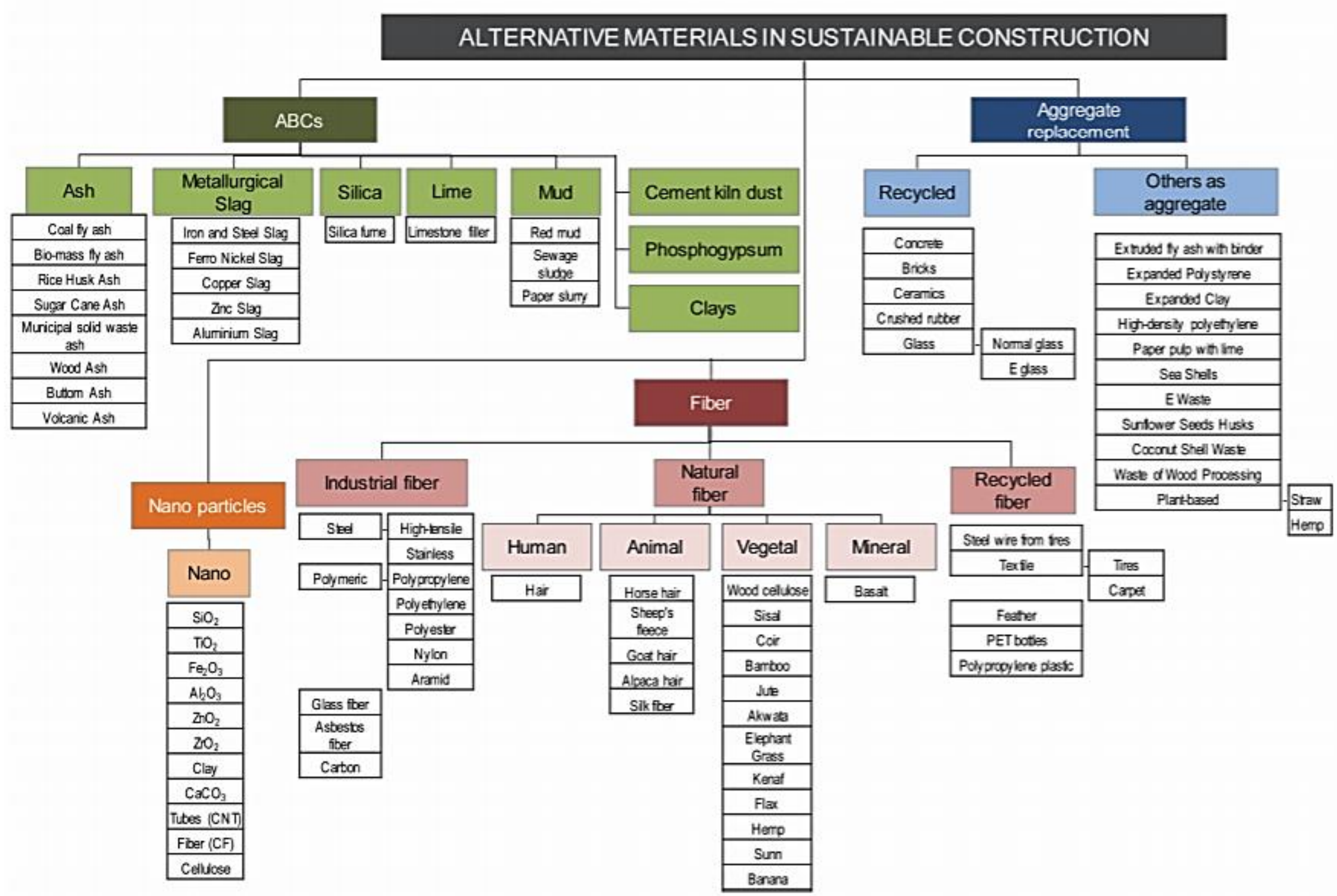

Figure 2. Overview of possible alternative construction materials, including alternative binders to Portland cement, (ABCs) in concrete.

(Source: Bjegovic D, Serda M. 2017. Alternative Materials in Sustainable Construction. Pp 1-18. In: Proceedings of the Proceedings of the 1st International Conference on Construction Materials for Sustainable Future, Zadar, Croatia, April 19-21, 2017)

Transformation: Alternatives to Cement

What about all of those alternative binders to cement? Unfortunately, many "green cement" ventures have become "vaporware," a terms for a software or hardware product that has been announced but never becomes commercially available, either because technical issues couldn't be resolved, investment didn't materialize, customers weren't buying, or the announcement itself was a PR stunt to dissuade users from changing platforms. For proposals for alternative binders to cement, vaporware is common.

Solidia®

Solidia® is a best case scenario for alternative binders. Founded in 2008, Solidia Technologies designed an alternative binder to cement that reabsorbs a greater amount of carbon dioxide during curing, producing up to 70% fewer CO_2 emissions than cement, at a comparable cost (Rathi 2017). The process replaces limestone with an artificially created version of the mineral wollastonite. Although Solidia envisioned Solidia cement (as opposed to Portland cement) as being a broadly applicable technology, the need to cure the Solidia cement in a high CO_2 chamber has narrowed ambitions to the production of precast concrete, such as bricks and slabs. However, by some estimates, precast cement like Solidia cement has the potential to supplant 15% of the global Portland cement market and up to 50% of the market where labor is expensive (Rathi 2017).

In 2019, LafargeHolcim and Solidia Technologies announced their first U.S. commercial venture, which was to supply a New Jersey paver and block plant with reduced CO_2 cement (LaFargeHolcim 2019).

Of course, questions remain. Will this commercial venture remain successful as it scales up? Will the headline-grabbing accomplishment of "up to" 70% CO_2 savings be fully realized or will Solidia's more tempered claim of CO_2 savings range from 30 to 70%, depending on the process adopted, be the outcome? Will Solidia cement replace 15% or more of the global cement market?

Novacem

A worst case for vaporware is illustrated by the rise and fall of U.K. based Novacem. Novacem developed a novel cement, alternative to Portland cement, based on magnesium oxide and hydrated magnesium carbonates with a reported negative carbon footprint. In 2010, Novacem received Material ConneXion's award for Material of the Year for 2010, and was recognized in *Technology Review* and the *Wall Street Journal* (Ceramic Tech Today 2011). Worryingly however, a *Ceramic Tech Today* reporter noted, "One perplexing thing about this product is that there doesn't appear to be any independent research on the properties of the Novacem cement, and that would be important to examine, for example, the durability and water-resistance of Novacem's product compare with Portland-based cement. So, some caution must be exercised in regard to accepting their claims" (Ceramic Tech Today 2011).

In 2012, Novacem sold out the intellectual product to a rival, Australia's Calix. In 2015, an article in a peer-reviewed journal noted, "As far as can be determined from the level of publications, no-one else is currently continuing to do research on the type of binder that

Novacem had been trying to develop" (Gartner and Hirao 2015). In the spring of 2020, a search of the Calix website (https://www.calix.com/) for "Novacem" produced no search results and the wordmark (the trademarked word logo) was listed as "abandoned" by the U.S. Patent and Trademark Office.

Calera

California-based Calera attempted to bring to market what they reported to be a carbon negative alternative cement binder (alternative to Portland cement) and they raised millions of dollars towards that effort. In 2009, skeptics scrambled to determine just how the technology worked. The patent application did not specify key parts of the process, but investor Alex Kinnier explained, "I can take CO_2 – and I don't have to separate out CO – and put that through sea water and sprinkle some pixie dust, and I can get calcium carbonate and magnesium carbonate out of that" (Kanellos 2009). Eventually, Calera moved into the market for niche applications like wallboard.

CarbonCure Technologies

The Canadian company CarbonCure Technologies approach replaces some of the cement with an injection of carbon dioxide, which then chemically transforms into calcium carbonate. In 2019, a CarbonCure press release announced, "The CarbonCure Technology is available in 126 concrete plants across the United States and Canada. The company recently announced its initial foray into international territories with an additional 3 plant installations at Pan-United, the leading concrete producer in Singapore." According to a press report, "One user, over the course of a single week after the technology was installed, saw its carbon dioxide emissions drop from 124.5 metric tons (137 tons) to 119 metric tons (131 tons)" (Berg 2016). So, this is about a 4.4 % reduction in carbon dioxide at that site. In 2020, the company website (https://www.carboncure.com/) features a map of the locations of CarbonCure masonry, precast, and ready mix producers, predominantly in the U.S. and Canada.

Summary of Alternative Cements

There are many other proposed alternatives to Portland cement. Those addressing precast applications for concrete seem to have made some headway. The key to transformation in the cement market will be adopting policy initiatives that are technology neutral and performance based.

The Sierra Club supports adoption of construction materials that have a low carbon footprint, that are made from sustainable raw materials and with renewable energy sources, that prevent waste by design rather than managing it after-the-fact (Sierra Club Zero Waste Policy), and that are safe and reliable for their intended use. We want sufficient technical information about the raw materials, the impact on worker health and safety over the life cycle of the material, manufacturing process, and product performance for stakeholders to be able to evaluate the product. And, as the Sierra Club, we recognize that others experiencing differing environmental impacts and those from different cultures, politics, or organizations have their own interests, and we have committed to working together with others for a common understanding under the Jemez Principles for Democratic Organizing.

3 Cement Industry Roadmap: Tinkering and Transition

The International Energy Agency and the Cement Sustainability Initiative (IEA/CSI), an industry group of 24 major cement producers[1] accounting for about 1/3 of the world's cement production and operating in more than100 countries, identified carbon emission mitigation levers in their recent Technology Roadmap report (IEA/CSI 2018a, 2018b). Their plan describes steps needed to achieve CO_2 reductions consistent with at least a 50% chance of limiting the average global temperature increase to 2°C above pre-industrial levels by 2100 (the "2DS"). Estimating anticipated growth of the industry globally, "Realising the sustainable transition of the 2 degree Celsius Scenario (2DS) implies a significant reduction of the global direct CO_2 emissions by 24% compared to current levels by 2050…" (IEA/CSI 2018a). So, we will first review the IEA/SCI Technology Roadmap, with the understanding that it is about tinkering and transition, not transformation.

What are the specific elements of the IEA/SCI Technology Roadmap? According to IEA/SCI, "The RTS serves as a baseline scenario for this roadmap. It considers energy consumption trends, as well as commitments by countries to limit carbon emissions and improve energy efficiency...Efforts made under the RTS would result in an average temperature increase of 2.7◦ C by 2100." In the roadmap, reductions in carbon emissions to conform to the 2DS depend slightly on thermal energy efficiency (3%) and fuel switching (12%), but mostly on clinker substitution with low carbon materials (37%) and, in the long-term, on the future development technologies such as carbon capture and storage (48%) for the industry (Figure 3). These reduction levers are reviewed below.

[1] CSI members: CEMEX, CRH, HeidelbergCement, InterCement, LafargeHolcim, SCG Cement, Taiheiyo Cement, Titan, Votorantim Cimentos, Cementos Argos, China Resources Cement, Cimenterie Nationale, Çimsa, China National Building Material, Dalmia Bharat Cement, GCC, Orient Cement, Secil, Shree Cement, Siam City Cement, Tianrui Cement, UltraTech Cement, West China Cement and Cementos Progreso.(IEA/CSI 2018b)

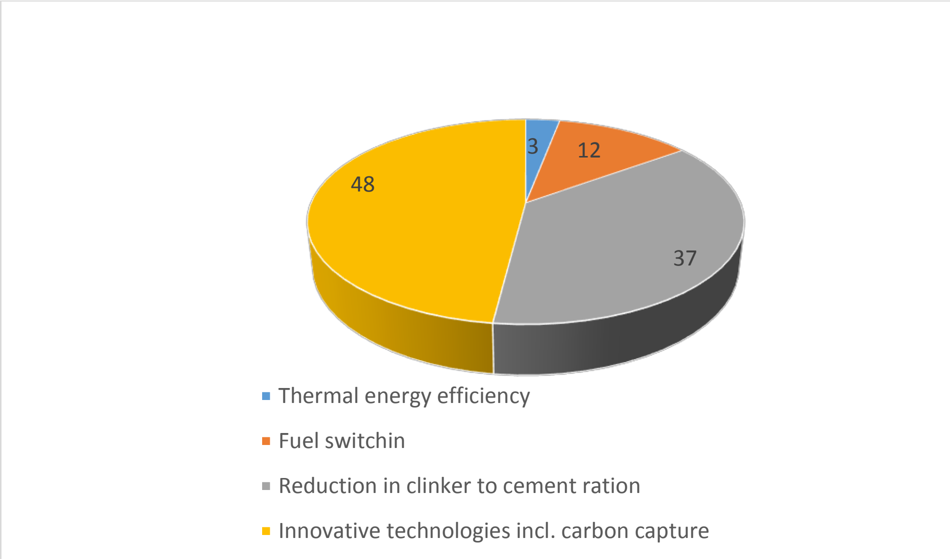

Figure 3. Contributions of Carbon Reduction Levers to the Percent Cumulative CO_2 according to the IEA/SCI Technology Roadmap.

3.1 Energy Efficiency

The steps needed to increase efficiency in cement production are well known and many have been implemented: "Between 1970 and 2010, primary physical energy intensity for cement production dropped 1.2% per year from 7.3 MBtu/short ton to 4.5 MBtu/short ton. Carbon dioxide intensity due to fuel consumption and raw material calcination dropped 24%, from 610 lb C/ton of cement (0.31 tC/tonne) to 469 lb C/ton cement (0.23 tC/tonne)" (Worrell et al. 2013).

More needs to be done.

EPA set out potential measures for addressing carbon and energy costs, with detailed cost, energy savings and emissions reductions, in "Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Portland Cement Industry" (US EPA, 2010). In 2013, EPA's Energy Star program published "Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making: An Energy Star® Guide for Energy and Plant Managers." Discouragingly however, the U.S. Geological Service (2020) reported that in 2019, "No major cement plant upgrades were completed during the year, but several minor upgrades were ongoing at a few domestic plants."

Both IEA/CSI and the Sierra Club support the adoption of excess heat recovery technologies and the adoption of renewable-based power generation. IEA/CSI recommends improving energy efficiency by using state-of-the-art technologies in new plants, with dry process kilns (with minerals dry ground to a powder) having both a *preheater* (a unit where the raw mix is heated, and the CO_2 and water driven off, before the mix is fed into the kiln) and a *precalciner* (a preheater booster that burns extra fuel at the base of the preheater to increase the preheater's thermal processing efficiency). Sierra Club supports using state of the art technologies for new plants.

There are two main types of processes for grinding and blending the materials that will go into the kiln: the wet process and dry processes. Both the Sierra Club and IEA/CSI support phasing out long dry kilns and wet process kilns. Sierra Club's recommends that wet kilns should shuttered, and long-dry kiln operations should be updated or shuttered.

According to industry sources (Bohan 2019), of the 128 kilns at the 91 U.S. cement plants, just 10 wet kilns remain in operation. The energy intensity for wet and the three kinds of dry kilns is shown in the Table 1, below (U.S. EPA 2010), with much lower energy intensity demonstrated for the various dry processes. In addition, the carbon dioxide intensity (kgC/st) for wet process kiln feed is 249 while for the dry process kiln feed it is 224.2 (Worrell and Galitsky 2004). Among the dry kilns, EPA estimates that conversion from a long dry kiln to a preheater/precalciner kiln could save 50-460 lb CO_2/ton cement.

Table 1. Typical Average Heat Input by Cement Kiln Type

Kiln Type	Heat Input, MMBtu/ton of cement
Wet	5.5
Long Dry	4.1
Preheater	3.5
Preheater/Precalciner	3.1

3.2 Fuel Switching

The kilns generate most of the carbon emissions, and many fuels do not generate sufficient thermal energy to drive the processes that occur in the kiln. Renewable-based power generation can reduce the 10% of carbon emissions that are generated by equipment ancillary to the kiln, such as grinders, crushers, mills, and conveyors. Looking at the range of alternative fuels, one is struck by the corollary to "where there is smoke, there is fire," which is "where there is fire, there is smoke." All energy production based on combustion is going to create and aerosolize pollutants, and all combustion releases carbon into the atmosphere, in biogenic or fossil form. So, while we can consider various proposed fuel switching alternatives, it is only non-combustion energy resources that have the potential to provide clean energy.

3.2.1 Municipal Solid Waste

The IEA/SCI fuel switching includes waste materials. The Sierra Club opposes burning of municipal waste (Sierra Club Energy Resources Policy) for fuel due to the hazardous air emissions. The Sierra Club opposes combustion of municipal waste for energy recovery, for treatment, and for disposal because the some of its non-biogenic components, such as plastic and metals, emit hazardous emissions and fossil carbon upon combustion. Combustion of mixed waste is often portrayed as an "alternative" to fossil fuel because these wastes contain some biogenic component. Of the combustible portion of the waste, plastics and petrochemical-based textiles and products make up part of the waste while biomass materials accounts for about 64% of the weight (U.S. Energy Information Administration 2019). However, moist biomass, such as food waste and yard trimmings, limits the heat energy value.

3.2.2 Tires

Tires reportedly contains biogenic carbon 18–22% for passenger car tires and 29–34% for truck tires from components such as natural rubbers and rayon [Rodríguez et al. 2017). Tires also contain metals and petrochemical products, which create hazardous emissions. Chlorine from tires permits the formation of hydrochloric acid, polychlorinated dibenzo-p-dioxins ("dioxin") and polychlorinated dibenzofurans ("furans").

Proponents claim that burning tires keeps them out of landfills; half of waste tires in the U.S. are burned In Arizona, however, cement kiln burning of tires was ended by 1990 and now 70 % of Arizona's scrap tires go into paving, a use that keeps the fossil carbon sequestered (Sousa J et al. 2007). So, rather than reducing the carbon footprint, cement kiln tire burning can serve as a disincentive to material recycling of tires.

3.2.3 Hazardous and Industrial Waste

The Sierra Club opposes the combustion of hazardous waste, industrial waste, medical waste, solid waste, including petrochemical waste, and other waste or fuel with non-biogenic components for fuel, for treatment, and for disposal due to the emission of fossil carbon and hazardous pollutants. Proponents of waste combustion often claim that emissions are cleaner or no worse than fossil fuel emissions in well run systems. However, such claims are negated by the codicil "in well run systems" that is routinely attached to such claims. In the United States, the cement industry has an abysmal record of managing and operating their systems. They depended for decades on a "Startup, Shutdown, Malfunction" (SSM) loophole in federal air pollution regulations that enabled the industry to belch out uncontrolled emissions under a broad set of exemptions and left communities routinely doused with particulate matter released from kiln stacks. In 2008, Earthjustice argued *Sierra Club v. U.S. EPA* (Case No. 02-1135, Dec. 19, 2008) in D.C. federal district court. The court found the loophole was indeed in violation of the Clean Air Act. However, in 2019, the State of Texas, host to a bevy of cement plants, was still trying to chip away at corrections made to the SSM rule (National Law Review 2019). Regulators, state and federal, have an abysmal record of enforcing permit limits. U.S. EPA has continued to pump out lax, subpar emissions standards for decades. For example, in 2011, the EPA's

Figure 4. Holnam Cement Belching Emissions over Ada, Oklahoma, 1995. (MJ Sinclair)

new mercury standards for cement kilns exempted kilns that burn hazardous waste for fuel from the standards (Berkes 2011). So, claims of the benign character of waste combustion premised upon "well managed and operated" systems are nullified (Figure 4). These waste burning facilities are dirty, willfully so, and they continue to be coddled by regulatory agencies.

According to U.S. EPA, the benefits of hazardous waste combustions are "reduced energy requirements and additional revenues from tipping fees paid by generators or fuel blenders to kilns for managing the hazardous waste" (U.S. EPA. 1999). The practice of "fuel blending" and the financial incentive of tipping fees to use cement kilns for waste disposal (under the guise of energy recovery) undermine fuel savings and emissions reductions. As described by the Ohio EPA (2018), "An example of fuel blending includes mixing a chlorinated solvent that has a lower British thermal unit (Btu) with a high Btu material to make the chlorinated solvent with the lower-Btu value amenable for energy recovery." So, some fossil fuel might be displaced – but some fossil fuel is being used generate the energy needed for waste disposal.

3.2.4 Biomass

IEA/SCI supports sustainable biomass as fuel. The Sierra Club opposes relying on logging or the use of municipal waste to produce biomass energy (see Sierra Club's Energy Resources Policy). Dedicated feedstocks that increase logging and displace forests or other wildlands can generate substantial carbon emissions and reduce existing carbon stores (see Sierra Club's Climate Resilience, Carbon Dioxide Removal, and Geoengineering Policy for an extensive discussion). Echoing concerns about sustainability, the cement giant LaFarge, which has been investigating biomass fuel production for over a decade, identified three non-financial barriers to biomass use: low energy density, reliable sourcing, and sustainability as demand increases [http://www.cement2020.org/content/about]. As for financial considerations, Friedman et al. (2019) found biomass in general to be more expensive than current fossil and waste fuels currently.

Biomass fuels that are used as part of the fuel mix by some cement plants around the world include agroindustrial wastes such as coffee husks, cotton stalks, saw dust, castor husks, and chat stem (Seboka et al. 2015), and also animal meal, wood chips and waste wood, rice husk, sawdust, and sewage sludge (Pembina Institute and Environmental Defence 2014). However, most biomass fuels do not have sufficient caloric value for the main firing of the kiln and would have to be mixed with more caloric fuels (U.S. EPA 2010). In cement manufacturing, lower carbon intensity processes (quarrying, transport, grinding, cooling, mixing, conveying, packaging) that are more amenable to low density fuel account for less than 10% of carbon emissions while the kiln, which requires high energy density fuel, accounts for about 90% of carbon emissions (40% from thermal emissions and 50% from the release of CO_2 via the heat-driven calcination process that converts limestone to lime) (Rodgers 2018; other estimates vary).

Biomass fuel is not pollution free. Biomass can contain more nitrogen then coal so the NOx pollutants can increase; NOx pollutants contribute to the formation of smog, acid rain, and particulate pollution. There are also pollution risks associated with sewage sludge. The sludge can be contaminated with human and animal pathogens that pose a risk of infection to those transporting and handling the waste. In combined sewer waste, which carry domestic and industrial waste, sewage sludge can contain metals (including lead, cadmium, zinc, mercury, and copper) and persistent organic pollutants (including pesticides, timber treatment, solvents) (MPA 2019), which can generate hazardous air pollutants. So, sewage sludge is a low carbon fuel, but not a clean fuel.

Fuel substitution with biomass cannot address the bulk of the fossil carbon emissions from cement manufacture.

3.3 Clinker substitution

According to U.S. EPA (2010), "In general, the use of 1 ton of material reduces emissions by the amount generated to produce 1 ton clinker." Clinker substitution as widely practiced around the world by the cement industry relies upon substituting some of the clinker with the byproducts of intensive fossil fuel driven industries, including the cement industry (cement kiln dust), power plants (fly ash), and iron and steel making (blast furnace slag). LafargeHolcim plans to increase its use of clinker substitutions from 25% to 35% from 2019 to 2022 (Patel 2019) A 2011 report identified fly ash as 8% of North American concrete and 25% of European concrete (Glazer et al. 2011). However, in mass concrete for dams, pavements, and parking lots, fly ash can constitute up to 70% by weight of cement (Rosenberg 2010).

EPA (U.S. EPA 2010) has estimated that substituting limestone with fly ash or steel slag or with calcareous oil shale could reduce emissions by .02 to 0.51 ton CO_2/ton clinker or by .009 ton CO_2/ton clinker, respectively. However, this projection is likely outdated because fly ash and slag are now being imported into the U.S. from overseas. Coal ash has been imported from China, Poland, and India (Rankin 2017). Much of the ground granulated blast furnace slag consumed in the United States is imported; from 2015 to 2019 imports steadily increased from 1.5 to 2.3 million metric tons (U.S. Geological Survey, 2020). So, one must add the generation of carbon from transportation by rail and ship to the carbon equation. Kisic et al. (2018) found that the "Use of alternative materials in developed markets is facing constrained supply. European companies will need to find scalable and sustainable alternatives to fly ash and slag or develop low-carbon technologies to be able to improve current emission intensity levels." So, supply is already a constraint.

Ground limestone, and, where available, some natural pozzolans (materials with cementitious attributes under certain conditions) such as volcanic ash or calcined clay, calcined shale, or metakaolin (a special clay that which could be mined or produced from Alberta oil sands tailing ponds) could also substitute for clinker. Emissions, however, must be controlled. In the near term, the IEA/SCI Technology Roadmap is paved with clinker substitution from non-sustainable, carbon intensive industries. In the quest to achieve full decarbonization, continued dependence on by-products of fossil fuel combustion is a stumbling block, not a stepping stone.

The Sierra Club opposes the use of fly ash and steel slag to concrete based on environmental justice and pollution prevention considerations. The use of fly ash and steel slag in concrete does not support the Sierra Club's long-range policy goal priorities to end pollution, which are to end the production of polluting substances and waste (zero waste); to prevent any release of polluting substances; to prevent exposure of plants, animals, or humans to polluting substances; and to remediate the effects of any such exposure (Sierra Club Environmental Justice Policy). The production of waste by the coal and steel industry is how fly ash and steel slag are generated; monetizing the waste supports its future generation. The handling of the waste by the cement industry then causes the pollutant to be released into the environment and to expose people to the pollutants. In the United States, the practice is to mix the clinker with the industrial waste at ready-mix cement plants rather than at the site of cement manufacture. The working class, low income, and minority communities so often hosting these facilities are plagued by noise pollution, emissions and road dust from heavy diesel traffic and the particulate matter generated by grinding, milling, mixing, packaging, loading and transport. These facilities sometimes mislead communities as to the nature and extent of the facility, greenwash their activity as climate friendly, and break promises made to communities to implement mitigation steps. As implemented in many communities, clinker substitution is occurring in an unjust way and perpetuates industrial waste generation.

3.4 Carbon Capture and Storage

The IEA/CS advocates integrating carbon capture and storage into the manufacturing process as a lever for decarbonization of the cement industry.

The Sierra Club has two concerns regarding this lever for carbon reduction in the cement industry. The Sierra Club (2020) Climate Resilience, Carbon Dioxide Removal, and Geoengineering Policy is extensive and should be consulted directly, but it includes the point that direct air capture should only be considered in parallel with the most aggressive accepted decarbonization policy.

Is CCS part of an aggressive decarbonization policy? Kisic et al. (2018) found that, "CCS is an important technology for this sector's decarbonization but remains at pilot stage. Heidelberg Cement leads the main projects in this space, with only limited R&D spend on CCS outside Europe." A project examining decarbonization options for the UK cement industry concluded, "...CCUS is not yet proven at the industrial scale in cement production and unlikely to be cost effectively deployed for several years, if not decades" (MPA et al. 2019). In other words, CCS remains a small scale, short term feasibility test, not a deployment of mature technology.

Some technologies are being explored that are specifically designed to remove the CO_2 from the limestone in the calciner (MPA et al 2019). MPA et al. (2019) speculate that if CO_2 capture from the calciner were paired with a carbon-free fuel source in the kiln, decarbonization of cement manufacture could be realized. These technologies should be explored, but the repeated reliance on speculative CCS technology by the cement industry might forestall more aggressive attention to the industry's ongoing glut of fossil carbon emissions. So, in this regard, CCS remains a question rather than an answer.

3.5 Summary

The IEA/CS proposes a plan with a 50% chance of reducing emissions to a level compatible with a 2DS. To achieve a 1.5DS (1.5 degree scenario), CO_2 reductions from fossil fuel use and industrial process emissions by industry would have to be reduced almost twice as fast as is required by the 2DS (Gambhir 2019). Sierra Club supports a 1DS (1 degree scenario), limiting the average global temperature increase to 1°C above pre-industrial levels by 2100, a goal that would require even greater reductions. Where does the IEA/CS roadmap take us?

The IEA/CS (2018b) summarizes this key point in their full report. Without the active steps recommended in the roadmap, "Direct CO2 emissions from the cement industry are expected to increase by 4% globally under the International Energy Agency (IEA) Reference Technology Scenario (RTS2) by 2050 despite an increase of 12% in global cement production in the same period." In the roadmap, "The integration of emerging and innovative technologies like carbon capture and reducing of the clinker content in cement are identified to provide the largest cumulative CO_2 emissions reductions in the 2DS compared to the RTS by 2050, with 48% and 37% contributions, respectively." So, roughly half of the CO_2 reductions rest on "emerging and innovative technologies" and "carbon capture." The roadmap depends upon technologies that are not yet deployable; they are concepts or drawing board sketches, or technologies tested on a limited, small scale or not at all.

As far as it goes, the roadmap features some good ideas. In the end, however, the roadmap depends upon emerging technologies and carbon capture – a road that is not yet there.

4 Alternative Energy Sources

Cement kilns have very specific heat requirements. At this time, the top three alternative energy sources to consider are biomass, resistive electricity, and hydrogen (Sandalow et al. 2019, Friedman et al. 2019). A recent entry, solar energy, is also presented.

4.1 Resistive Electricity

"Cement kilns work better with energy-dense internal fuel; resistive electricity on the outer surface doesn't work as well" (Roberts 2020). However, others have made a case for resistive electricity being adaptable to supplying energy to the precalciner (MPA et al. 2019). The technology is unproven for cement industry applications and the list of research needs laid out by MPA et al. remains daunting.

4.2 Green Hydrogen

Green hydrogen fuel is produced via water electrolysis that is driven by clean renewable energy sources such as solar and wind. Currently, about 0.1 % of hydrogen energy is generated by water electrolysis (IEA 2019). Hydrogen power being produced today is hydrogen fuel created by processing fossil-fuel and emitting the resulting carbon into the atmosphere (Wouters 2020).

Currently, green hydrogen energy is expensive to produce, about double the cost of petrochemical hydrogen (Roberts 2020) but IEA (2019) predicts that the cost of green hydrogen could decline 30% by 2030 with the declining cost of renewable energy, the potential for scaling up hydrogen production, and building out existing infrastructure.

For energy-intensive manufacturing such as cement manufacture, "the heat has to be high-temperature heat and large amounts of heat must be delivered steadily, reliably, and continuously" (Roberts 2020). Hydrogen burned in air does provide sufficient heat to drive cement manufacture, but the use of the process in cement making has not been researched (Sandalow et al. 2019). The various technical barriers – including storage of the explosive gas, replacement of equipment, changes to the process, and impact on product quality – are spelled out in Hoenig et al. (2007). Sandalow et al. (2019) conclude that, because green hydrogen use would not diminish carbon emissions from the raw material limestone, the use of green hydrogen instead of fossil fuel in cement production would reduce up to 30% of carbon emissions but, at present prices, would triple the cost of clinker production. If the grid were carrying green energy, then the potential to produce green hydrogen could be realized. In the case of green hydrogen energy, the view of Roberts (2020) applies:

> It all gets easier if clean power gets cheaper. It's true of resistive electricity, it's true of green hydrogen, and it's true of almost all the difficult to decarbonize [industrial] sectors. Cheap, abundant, clean electricity is the only road to a genuinely sustainable energy system unified around the grid and the free exchange of electrons.

So, while green hydrogen has the potential to play an important part in the manufacture of greener building materials, it is not a ready solution to carbon emissions from Portland cement manufacture.

4.3 Here Comes the Sun?

As noted, cement manufacture has very specific requirements for temperature and how that heat is applied. So, this announcement (Rathi 2019) should elicit inspiration and skepticism, in equal parts:

> A new solar startup, funded by billionaires Bill Gates and Patrick Soon-Shiong, believes it has an alternative. Heliogen has come out of stealth mode to showcase a technology that can focus the sun's beams to achieve temperatures as high as 1,500°C—far beyond those reached by current technology. That's high enough, in theory, to provide the heat needed to make cement, convert biomass into biofuels, and perhaps even extract hydrogen from water.

5 The Construction Industry and Climate: Transformation

What policy approaches should be employed to bring about the decarbonization of the construction industry?

Many of the general approaches to decarbonization of the construction industry are detailed in the Sierra Club (2020) Climate Resilience, Carbon Dioxide Removal, and Geoengineering Policy, which covers environmentally beneficial approaches to addressing climate change. To address contribution of the cement industry to global climate change, cement industry, the Sierra Club supports:

- the use of natural systems to accomplish building and engineering goals
- supports a just transition to decarbonization
- transition of cement manufacturing from fossil fuel to renewable energy
- supports the adoption of sustainable low carbon building materials
- novel approaches to engineering, architecture, and building technology that reduce the use of carbon intensive construction materials while maintaining energy conservation of the built structures
- updating building codes and material specifications so that safe low-carbon alternative building designs and materials can compete in the market place
- government purchasing practices, tax codes, and economic policies that advantage sustainable low-carbon construction
- reducing the carbon footprint of cement manufacturing by the shutdown wet and long kilns; deployment of state-of-the art energy efficiency technology; use of non-fossil fuel derived, clean, renewable, sustainable fuels; banning of cement kilns for waste treatment and disposal; and use supplemental cementitious materials, with the understanding that continued dependence on by-products of fossil fuel combustion is a stumbling block, not a stepping stone, to decarbonization.

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