Industrial Decarbonization Roadmap, Cement Manufacturing

By John Benson

March 2023

1. Introduction

The first part of this post was an Overview and is linked below:

https://energycentral.com/c/cp/industrial-decarbonization-roadmap-part-1-overview

Part 2 was about Iron and Steel Production Industries and is linked below.

https://energycentral.com/c/ec/industrial-decarbonization-roadmap-part-2-iron-steel

Part 3 was about Chemical Manufacturing and is linked below.

https://energycentral.com/c/cp/industrial-decarbonization-roadmap-part-3-chemical-manufacturing

Part 4 was about the Food and Beverage Manufacturing Industry, and is linked below.

https://energycentral.com/c/ec/industrial-decarbonization-roadmap-pt-4-food-and-beverages

Part 5 was about Petroleum Refining, and is linked below.

https://energycentral.com/c/og/industrial-decarbonization-roadmap-pt-4-petroleum-refining

Part 6 is on Cement Manufacturing. *In 2020, the United States produced 87 million metric tons (MT) of Portland cement and 2.3 million MT of masonry cement at 96 plants in 34 states.[1] Of those, 86 plants employed the dry kiln process and nine used the wet kiln process.[2] In 2020, sales of cement were around $12.7 billion and consumption was about 102 million MT. Texas, Missouri, California, and Florida have the highest cement production, in that order, and they account for about 45% of U.S. cement production.*

I have written on this industry before (in 2018):

Concrete Greenhouse: *This paper is about the cement and concrete industries, their energy use, greenhouse gas (GHG) emissions, and how they might reduce the emissions in the future.*

https://www.energycentral.com/c/cp/concrete-greenhouse

The Primary reference for this paper is here.[3]

---

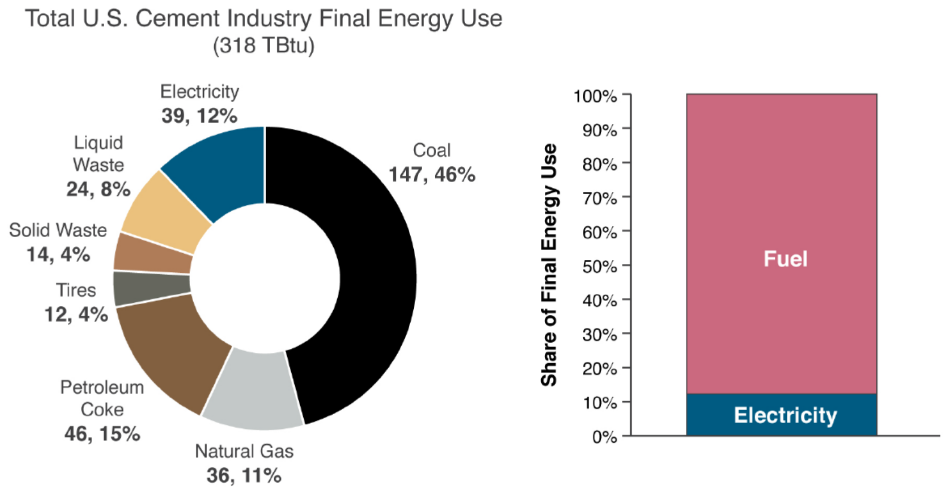
[1] Ashley K. Hatfield, Mineral Commodity Summaries: Cement, U.S. Geological Survey, January 2021, https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-cement.pdf

[2] Ali Hasanbeigi, Dinah Shi, and Harshvardhan Khutal, Federal Buy Clean Policy for Construction Material in the United States, 2021, https://www.aceee.org/sites/default/files/pdfs/ssi21/panel-4/Shi.pdf

[3] Full List of authors, reviewers and supporting groups is contained on this document's front-matter pages xi -- xiv, U.S. Department of Energy, "Industrial Decarbonization Roadmap," September 2022, https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf

2. Current Energy Use & Emissions

In 2015, the U.S. cement industry used around 279 TBtu (1 TBtu = 1 Trillion Btus or roughly 293,000 MWh) of heat from fuel combustion and 39 TBtu (11,427,000 MWh) of electricity (see figure below), which represented a 19% decrease in fuel consumption and a 9% drop in electricity consumption from 2000.[4] The drops in energy use were primarily due to upgrades to more energy-efficient production technologies, retirement of a few older inefficient plants, construction of a few new state-of-the-art plants, and a slight (around 4%) reduction in U.S. clinker and cement production from 2000 to 2015…



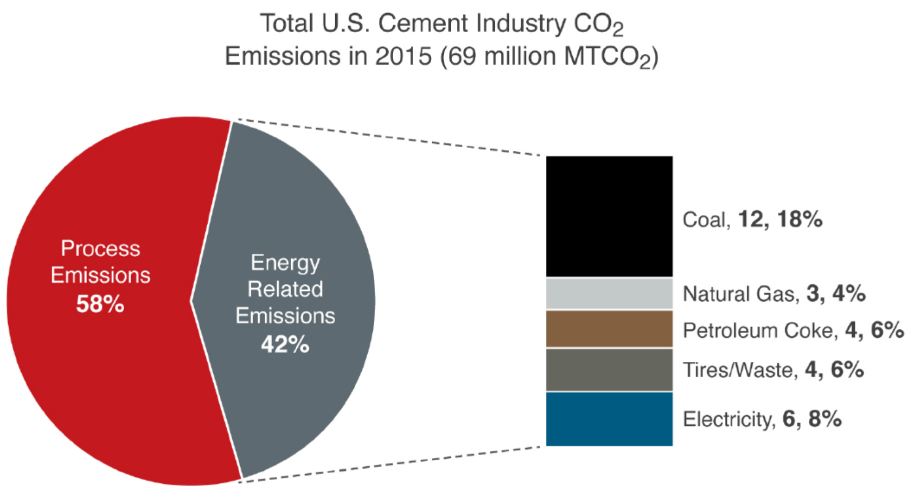
***Note:** recent U.S. Geological Survey (USGS) data show that the share of natural gas consumption by the cement industry increased to 46% and coal consumption decreased to 15% between 2015 and 2016 and that both remained at these levels in 2017. USGS data provides a breakdown of fuel sources that are not available from other public data sources. Data source: USGS 2020.[5]*

In the U.S. cement industry in 2015, process-related CO_2 emissions from calcination accounted for 58% of total CO_2 emissions and energy-related CO_2 emissions accounted for 42% of total emissions. In other words, 58% of the CO_2 emissions from the U.S. cement industry were not associated with energy use (figure below).[6] Therefore, decarbonization in the cement industry cannot be achieved by the best available energy-efficient technologies or fuel switching alone. Deployment of technologies such as carbon capture, utilization, and storage (CCUS) and innovative chemistry will be imperative to achieving near zero GHG emissions in cement production. Another key consideration is that electricity currently accounts for only 8% of total the U.S. cement industry's GHG emissions.

[4] Hendrik G. van Oss, 2015 Minerals Yearbook: Cement, U.S. Geological Survey, September 2018, https://d9-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2015-cemen.pdf

[5] Clinker produced and fuel consumed by the U.S. cement industry by kiln process. Energy data from 2015 were used as the base line for the scenario analysis conducted as part of this decarbonization roadmap. See Table 7 of Hendrik G. van Oss, 2016 Minerals Yearbook: Cement, U.S. Geological Survey, January 2020, https://d9-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2016-cement.pdf

[6] Ali Hasanbeigi and Cecilia Springer, Deep Decarbonization Roadmap for California's Cement and Concrete Industry, Global Efficiency Intelligence, September 2019, https://www.globalefficiencyintel.com/decarbonization-roadmap-california-cement-concrete



Additionally, cement manufacturing generates significant air pollutants (such as sulfur dioxide, nitrous oxide, or non-methane volatile organic compounds), which contribute to adverse health effects and can negatively impact their local communities (typically in low-income, disadvantaged communities).[7] *These air pollutants should be considered alongside GHG emissions as the cement industry decarbonizes.*

3. Basic Cement Manufacturing Processes

As I was going through the cement manufacturing section in reference 3, I noted a pretty serious issue. First of all, this is the last industry where they the authors took a deep dive, and it has very complex processes that use unique terms. I really don't believe the authors spent enough time delving into these processes, but instead dived directly into their proposed fixes. The good news as I was starting on this paper, I was also reading my Feb 2023 hardcopy issue of Scientific American, and it has a brief article that covered the same ground. Also this article did an excellent job of explaining the processes as well as potential fixes for each process. I looked on-line, and there a reasonable version of this article (referenced below). Thus, this section will repeat much the Scientific American information about the processes and potential for CO_2 reduction.

3.1. Mine and Grind Limestone

How it works: *Deposits containing calcium carbonate, such as limestone or chalk, are mined from quarries, which may include small amounts of clay containing silicon, aluminum or iron. The ingredients are crushed into pieces less than 10 centimeters in size and then milled into a powder called raw meal.*[8]

Room to improve: *Start with basalt instead of limestone or use "carbon-negative limestone" produced with waste CO_2 (step 2), reducing emissions by up to 60 to 70 percent.*

[7] Ali Hasanbeigi, Navdeep Bhadbhade, and Ahana Ghosh, Air Pollution from Global Cement Industry: An International Benchmarking of Criteria Air Pollutants Intensities, August 2022, https://www.globalefficiencyintel.com/air-pollution-from-global-cement-industry

[8] By Mark Fischetti, Nick Bockelman, Wil V. Srubar, Scientific American. "Solving Cement's Massive Carbon Problem," February 1, 2023, https://www.scientificamerican.com/article/solving-cements-massive-carbon-problem/

3.2. Preheat Raw Meal

How it works: *Raw meal in a chamber above a kiln is heated to temperatures as high as 700 degrees C by the kiln's hot, swirling exhaust gases, driving off moisture.*

Room to improve: *Burn oxygen-rich air to lessen CO_2 emissions. Add equipment to capture CO_2, which could reduce emissions by up to 60 percent. Use the waste CO_2 to make carbon-negative limestone (see subsection 3.1). Burn biomass or waste to heat the kiln instead of fossil fuel.*

3.3. Convert Meal into Lime

How it works: *Preheated meal is burned in a combustion chamber immediately above and inside the top of the kiln at 750 to 900 degrees C, converting calcium carbonate to calcium oxide (quicklime) and CO_2. This step accounts for 60 to 70 percent of the CO_2 driven out of the raw materials and consumes about 65 percent of all fuel used in the entire cement production process.*

Room to improve: *Burn oxygen-rich air to lessen CO_2 emissions. Add equipment to capture CO_2. Use an electric kiln run on renewable energy, reducing emissions for subsections 3.2, 3.3 and 3.4 by 30 to 40 percent.*

3.4. Convert Lime into Clinker

How it works: *Lime is burned at up to 1,450 degrees C in a kiln rotating three to five times per minute. This process melts and sinters (fuses) the lime into Portland cement clinker—dark gray nodules three to 25 millimeters in diameter—and drives off more CO_2. Clinker is the binder that causes cement to harden when it reacts with water.*

Room to improve: *Add a mineralizer such as calcium fluoride or sulfate to lower the lime's melting temperature, saving energy.*

3.5. Cool and Store Clinker

How it works: *Hot clinker is run across grates where air blowers cool it to about 100 degrees C. Once cool, it is stored in a silo and can last a long time without degrading, so it may be sold as its own commodity.*

Room to improve: *Electrify the process or pipe in waste heat from step 3 for initial cooling.*

3.6. Blend Clinker with Gypsum

How it works: *Clinker is mixed with gypsum at a ratio of 20 or 25 to one.*

Room to improve: *Electrify the process.*

3.7. Grind the Blend into Portland Cement

How it works: *Roller mills or ball mills grind the clinker and gypsum into a fine gray powder known as Portland cement.*

Room to improve: *Add finely ground limestone to replace up to 35 percent of the cement, reducing emissions created during earlier production steps. This mix is known as Portland-limestone cement. Create "blended cements" by adding fly ash (20 to 40 percent), slag (30 to 60 percent) or calcined clay (20 to 30 percent) to lower the clinker-to-cement ratio, reducing emissions by similar percentages.*

3.8. House Cement in Silos

How it works: *The powder is thoroughly mixed so it is uniform throughout and is then stored in a silo. It will be packed into bags for retail sale or loaded into trucks headed for concrete mix facilities.*

Room to improve: *Consider lower-carbon alternatives to Portland cement for certain applications. These alternatives include alkali-activated cements and bio-cements generated by algae or microbes, as well as cements made from magnesium phosphate, calcium aluminate or calcium sulfoaluminate. Such options can reduce emissions for the entire process by 40 percent or more.*

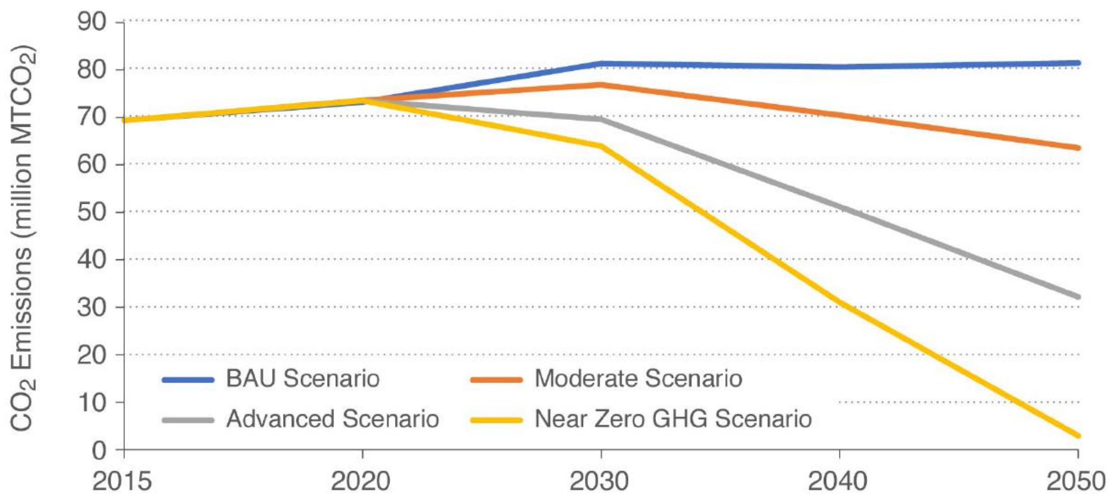
Author's comment: One more term: Portland cement is a fine gray powder that is manufactured as described above. Liquid concrete is created (normally in large trucks with rotating mixers on their aft-chassis) by mixing Portland cement with water and aggregate (sand and gravel and perhaps other substances in lieu of some/all of the sand and gravel. About 80% of the liquid concrete is aggregate). It then delivered to a construction site, poured (or pumped) and allowed to harden into solid concrete.

4. Decarbonization Pathways

To understand how application of the decarbonization pillars (energy efficiency, electrification, low-carbon fuels, feedstocks, and energy sources (LCFFES), carbon capture, utilization, and storage (CCUS)) could help phase out net GHG emissions, the potential CO_2 reductions for the cement industry were examined for each pillar. Electrification and LCFFES are highly connected and evaluated together for this roadmap. This roadmap also provides guidance on where research development and demonstration (RD&D) could enable substantial reductions in GHG emissions. The topics of where to start on reductions, the relative impact of the decarbonization pillars, and priorities for RD&D were also of common interest across the stakeholder meetings.

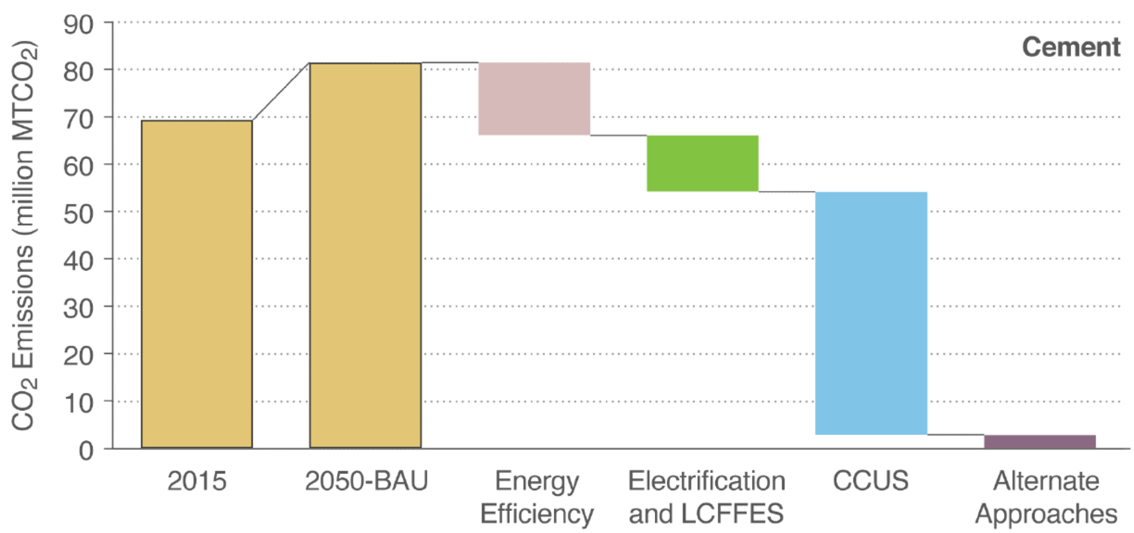
The figure below (next page) shows/describes a forecast of CO_2 emissions from the U.S. cement industry through 2050 for 4 scenarios: Business as Usual, Moderate Technology and Policy, Advanced Technology and Policy, and Near Zero GHG Emissions.

Various factors contribute to the realization of significant CO_2 emissions reductions in each scenario. The second figure below shows the contribution of the decarbonization pillars (energy efficiency, industrial electrification and LCFFES, and CCUS) to reduction in the U.S. cement industry's CO_2 emissions between 2015 and 2050 for the Near Zero GHG scenario. CCUS makes the largest contribution to CO_2 emissions reduction, followed by energy efficiency which also includes innovative chemistry (mainly replacing clinker with supplementary cementitious materials (SCMs) for cement production and extending the use of lower-carbon binders instead of Portland cement). The RD&D challenges and opportunities for each of the decarbonization pillars and technical requirements for their adoption in the U.S. cement industry are discussed in detail in the next section.



CO_2 Emissions Forecast for the U.S. Cement Industry by Scenario, 2015–2050.

The business as usual (BAU) Scenario assumes slow improvement; Moderate assumes higher rates of energy efficiency, switching to lower-carbon fuels, electrification adoption, and some CCUS; Advanced assumes even higher rates; and Near Zero assumes the most aggressive improvement and adoption rates.



Impact of the decarbonization pillars on CO_2 emissions (million MT/year) for the U.S. Cement Manufacturing Subsector, 2015–2050.

Subsector emissions are estimated for business as usual (BAU) and near zero GHG Scenarios. Since industrial electrification and LCFFES technologies and strategies are strongly interconnected, these pillars were grouped for scenario modeling. The "alternate approaches" band shows further emissions reductions necessary to reach net-zero emissions for the subsector. These alternate approaches, including negative emissions technologies, are not specifically evaluated in scenario modeling for this roadmap. The powering of alternate approaches will also need clean energy sources (e.g., direct air capture could be powered by nuclear, renewable sources, solar, waste heat from industrial operations, etc.).

4.1. RD&D Needs and Opportunities

4.1.1. Priority Approaches

To achieve the necessary decarbonization targets, the cement industry requires technology breakthroughs including new low-carbon manufacturing pathways, process electrification at scale, use of H_2, direct separation, carbon utilization and an enhanced circular economy approach for CO_2, and material reuse. Priority approaches include:

- *Leverage relatively low-capital solutions (energy efficiency, strategic energy management (SEM), and waste heat reduction/recovery solutions (WHP)).*
- *Probe routes to continue improving materials efficiency and flexibility including reuse, recycle, and refurbishment as well as innovative chemistry and blended cement with improved energy and emissions, CO_2 absorbing, and equivalent or better performance.*
- *Expand the infrastructure and integration capabilities and knowledge to capture, transport, and reuse CO_2 where possible (e.g., Oxy-combustion with CCUS, indirect calcination with CCUS, large scale carbon utilization for construction materials).*
- *Advance approaches to reduce waste, including the use of circular economy approaches for concrete construction.*
- *Increase use of low-carbon binding materials and natural supplementary cementitious material (SCMs).*
- *Develop additional routes for utilizing CO_2, including full scale deployment of carbon capture with innovative approaches such as calcium looping (see my comment in subsection 4.1.4 and subsection 4.1.5) and use of membranes for CO_2 separation.*

4.1.2. Energy Efficiency

Many energy efficiency technologies applicable to the cement industry are ready to be deployed on a commercial scale. These include waste heat recovery (WHR) for power technologies, multistage preheater/pre-calciner kilns, high-efficiency clinker cooling, and more-efficient grinding processes. However, challenges with deployment of these technologies remain and RD&D could help address them.

Increasing the efficiency of multistage preheater/pre-calciner kilns and clinker coolers comes with unique challenges. For modern five-stage pre-calciner kilns, about 60% of the heat goes into the required chemical reactions. The preheater recuperates heat from the combustion products and the cooler recuperates heat from the hot clinker. The preheater exhaust gases (at around 300°C or 572°F) are used to dry raw materials. The amount of excess heat available in these gases depends on the amount of drying required and can be affected by seasonal variations. The cooler uses approximately two kilograms of air per kilogram of clinker, about half of which is used for combustion air in the kiln. The other half can be used for waste heat recovery. Currently, heat losses through radiation are about 10% or less and this can be reduced through better insulation. There are some technical tradeoffs for improving efficiency in the kiln and clinker cooler; for example, the number of preheating stages could be increased to improve heat recovery, but at the cost of increasing electricity consumption. Increases in preheater efficiency are partially neutralized by accompanying decreases in cooler heat recovery.

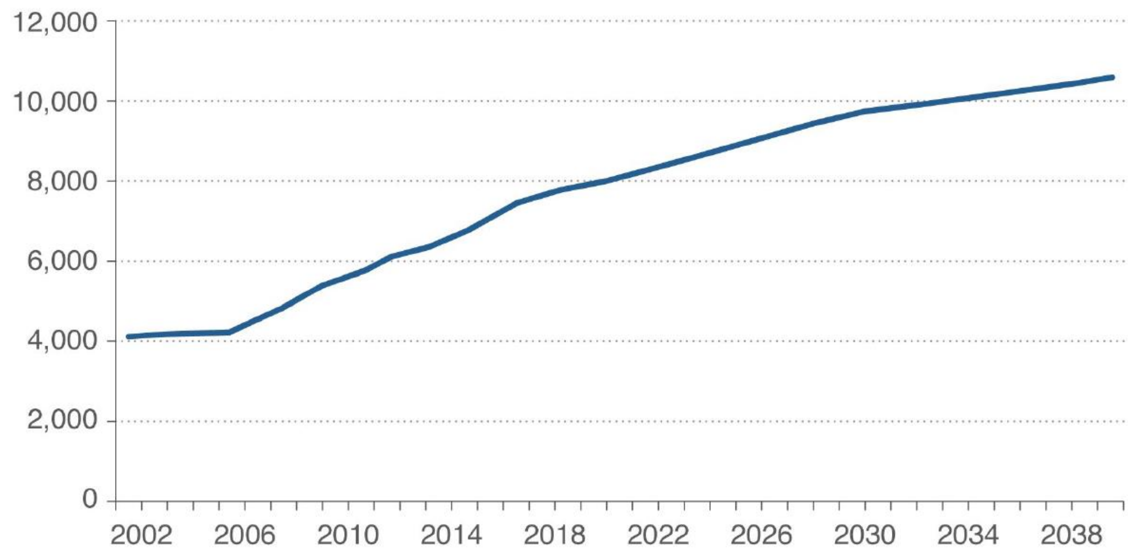
4.1.3. Innovative Chemistries

Innovative chemistry was identified during the stakeholder meetings and in subsequent written feedback from stakeholders as an important strategy to reduce GHG emissions from cement and concrete production. Innovative chemistry approaches include increasing the share of supplementary cementitious materials (SCMs) in cement (or concrete) production and using alternative binding materials. Substituting these materials for higher energy-consuming and CO_2-emitting clinker and Portland cement can reduce the energy and carbon footprint of cement and concrete. The Portland Cement Association notes that the common U.S. practice is adding less SCM during cement manufacturing and more SCM during the concrete batching process, whereas other countries tend to incorporate the SCMs during the cement manufacturing process. A variety of organic binders made from low-carbon materials that help to significantly reduce energy/GHGs of cement production may also be areas for RD&D.

In terms of technical challenges, for cement and concrete that incorporate a higher share of traditional SCMs, or use less common SCMs or alternative binders, questions remain about the ability of the final cement product to meet performance and durability requirements in certain construction applications. Market acceptance and economics are also major challenges for blended cements using SCMs. The use of SCMs largely depends on cost and regional availability of materials such as ground-granulated blast furnace slag (a waste product of primary steelmaking), fly ash (a waste product of coal-fired power plants), ground limestone, natural pozzolans,[9] and calcined clay. While existing stockpiles of coal fly ash can continue to be mined for use in cement making, given the expected declining availability of ground-granulated blast furnace slag and fly ash (and potential regulations on fly ash storage that make it difficult to maintain adequate inventory onsite), natural SCMs such as ground limestone, pozzolans, and calcined clay are likely to be an upcoming focal point. Acceptance of different formulations will require (1) RD&D to build confidence in the performance and cost of new formulations, (2) alignment with global best practices for higher use of natural SCMs in cement and concrete production, and (3) incorporation in U.S. or states' standards to increase the allowable level of SCMs use…

To address regulatory and economic challenges, techno-economic analysis could help decision makers better understand opportunities for SCM use, especially on a regional basis and for upcoming natural materials. Adoption of lifecycle assessment (LCA) by professional services (e.g., architects and engineers) could identify opportunities for different applications of SCMs to reduce the overall carbon footprint. More broadly, modeling is needed to investigate mid- and long-term supply availability of SCMs to understand how plants might use them cost-effectively. The Portland Cement Association projects that SCM use in cement production will grow by 2040 (figure on next page), but a more fine-grained understanding of the supply limits for specific types of SCMs is needed to overcome economic challenges.

[9] Pozzolans are a broad class of siliceous and aluminous materials which, in themselves, possess little or no cementitious value but which will, in finely divided form and in the presence of water, react chemically with calcium hydroxide ($Ca(OH)_2$) at ordinary temperature to form compounds possessing cementitious properties. Source: Wikipedia article on "Pozzolan."



Portland Cement Association projection of SCM use in cement production (vertical axis is thousands of metric tons).

4.1.4. Electrification, Low-Carbon Fuels, Feedstocks, & Energy Sources

Natural Gas: *Increased use of natural gas instead of coal and petroleum coke offers the potential to lower GHG emissions from cement plants in the near term. General challenges for increased natural gas use are related to infrastructure needs, as the basic technology is commercially available. Some cement plants are not near natural gas pipelines; even when pipelines are nearby, feeding off the main pipeline and bringing the gas to the plant can be difficult and costly. Utilities are often unwilling to take on the costs to build these connections. In urban areas, population density makes supply line connection a particular challenge. Uncertainty about consistency of supply, reliability, and cost can be a major barrier in some locations. In terms of the technology, some cement plants could require retrofits to the pyro-processing system because of differences in retention time. Higher nitrogen oxide emissions, higher gas volumes per introduced energy unit, and reduced production efficiency can be caused by increased natural gas usage and can only be mitigated by permit changes that some plants might be reluctant to file. However, the technical challenges can be overcome by available technologies, and other countries (e.g., Russia and Qatar) have large natural gas resources and use natural gas as the primary fuel in their cement kilns.*

RD&D could address infrastructure challenges by mapping the natural gas distribution infrastructure and identifying the optimal sites for fuel switching based on infrastructure and supply considerations. RD&D efforts to optimize kiln operations and burner design to minimize the effects of the different natural gas combustion characteristics could further accelerate the near-term adoption of natural gas. For example, research could focus on computational fluid dynamic modeling to address how to meet time-temperature requirements in new burners and redesigned calciner vessels. RD&D should also identify global best practices for using natural gas in cement plants and help transfer those lessons to the United States.

Author's comment: Many would argue against the approach described in the above two paragraphs. I believe we need to take a hard look at this and compare it with other "baby step" approaches described below. Every ton of CO_2 we can keep out of the world's atmosphere equates to a reduction in the worst effects of climate change.

Biomass and Alternative Fuels: *Increasing the use of biomass in cement kilns, which could lower GHG emissions from cement plants in the near and medium term, faces many similar challenges. For existing kilns, use of biomass is feasible up to a certain percentage. Increasing beyond that will require some RD&D. Transporting biomass to cement plants is often cost-prohibitive. In addition, biomass itself has significantly different combustion characteristics than coal and petroleum coke (e.g., a lower heating value), which means the calciners[10] may require multichannel burners and careful monitoring of impurities. Not all biomass is suitable for use in the kiln because of moisture content and high moisture content could require the use of more energy. Higher replacement rates of traditional fuel with biomass at the kiln would likely require drying and pyrolysis to achieve the necessary flame temperature.*

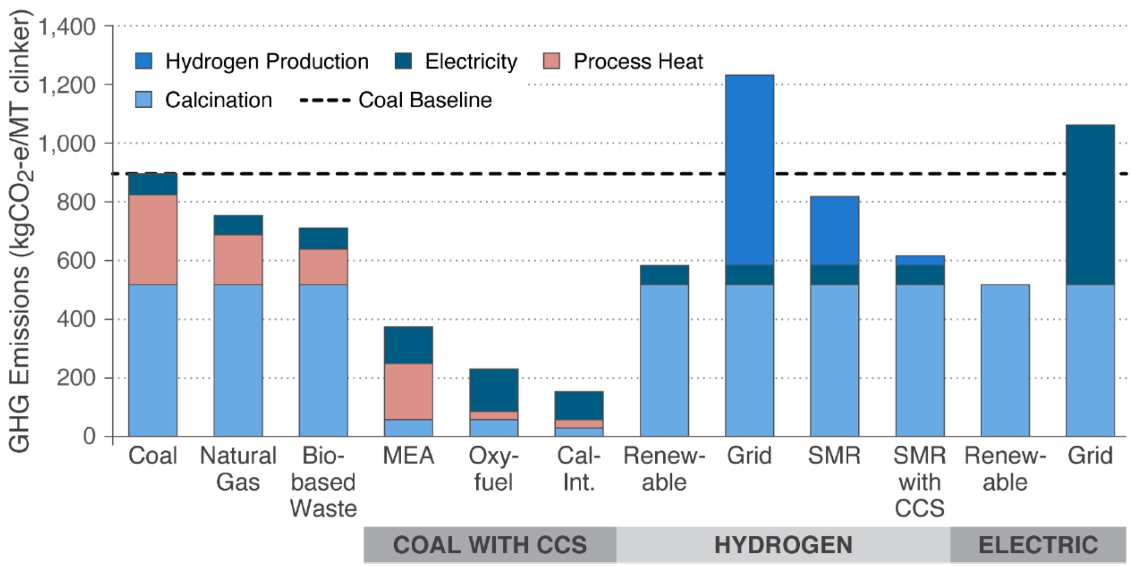
Regulatory issues for alternative fuels, including nonhazardous secondary materials, are also challenging; they include solid waste regulations that might prohibit cement plants from using certain alternative fuels, including biomass, waste plastics, wastepaper, and municipal solid wastes. Insufficient financial incentives exist today for diverting large amounts of combustible wastes from landfills to use in cement kilns. The outputs from alternative fuels, such as the types of emissions and waste they produce, are less well-understood than they are for conventional fuels and additional research is needed to improve the understanding of the public health implications for burning certain waste materials as fuel (e.g., plastics). In addition, there is still debate about whether biomass and some alternative fuels are low-carbon or carbon-neutral fuels.

Given the wide range of alternative fuel types and the various fuel mixes in use at cement plants, RD&D could help with cataloging what has already been done around the world (including collecting heating values for alternative fuels). For biomass, the Bioenergy Technology Office (BETO) funded Feedstock Conversion Interface Consortium (FCIC) has been researching fuel properties (e.g., heat values), life cycle impacts (e.g., GHG emissions), and techno-economic analysis of regional availability in the United States. The FCIC has also studied high moisture content biomass to identify efficient, cost-effective ways to use it under different torrefaction[11] scenarios (i.e., producing the most biomass fuel with the least energy input and best particle size distribution). RD&D has also been done to assess the bulk flow characteristics of the biomass supply chain, thus helping identify efficient transport, storage, and preparation pathways for the U.S. cement industry…

[10] The process of calcination derives its name from the Latin calcinare (to burn lime) due to its most common application, the decomposition of calcium carbonate (limestone) to calcium oxide (lime) and carbon dioxide, in order to create cement.

[11] Torrefaction of biomass, e.g., wood or grain, is a mild form of pyrolysis at temperatures typically between 200 and 320 °C. Torrefaction changes biomass properties to provide a better fuel quality for combustion and gasification applications.

RD&D could also help demonstrate the economic and GHG benefits of using biomass and low-carbon alternative fuels for cement production. For example, the CEMCAP project[12] and subsequent analysis extensions compared the carbon intensity of clinker produced from different fuel mixes, including natural gas, biomass, different types of hydrogen, and electrification (the latter two technologies are discussed below). The project found that biomass and natural gas had lower carbon intensity than the coal baseline (figure below). Additional research is needed to further explore the GHG benefits of alternative fuels. The figure below shows that process-related emission from calcination accounts for a substantial share of GHG emissions from cement plants and cannot be reduced by switching fuel to natural gas, biomass, hydrogen, or electricity. Carbon capture and storage (CCS) is required to capture process-related emissions. If clean hydrogen or renewably sourced electricity is used as fuel in the kiln and CCS is used to capture calcination-related CO_2 emissions, the GHG emissions intensity of clinker production can be brought down to zero or near zero.



Carbon intensity of clinker produced by different fuel pathways

This figure shows the GHG emissions in cement production when different types of fuels are used with or without CCSs. MEA – monoethanolamine,[13] SMR – steam methane reforming.[14]

Author's comment: I believe that "Cal-Int." pathway in the above chart refers to Calcium Looping Integration. Calcium looping, or the regenerative calcium cycle (RCC), is a second-generation carbon capture technology. It is the most developed form of carbonate looping, where a metal (M) is reversibly reacted between its carbonate form (MCO_3) and its oxide form (MO) to separate carbon dioxide from other gases coming from either power generation or an industrial plant. In the calcium looping process, the two species are calcium carbonate ($CaCO_3$) and calcium oxide (CaO). The captured carbon dioxide can then be transported to a storage site or used as a chemical feedstock. Calcium oxide is often referred to as the sorbent. Credit: Wikipedia article on calcium looping. Also see subsection 4.1.5 below.

[12] "CEMCAP," SINTEF, accessed 2021, https://www.sintef.no/projectweb/cemcap/

[13] Monoethanolamines can scrub combusted-coal, combusted-methane and combusted-biogas flue emissions of carbon dioxide (CO_2) very efficiently.

[14] David Sandalow et al., ICEF Industrial Heat Decarbonization Roadmap, Innovation for Cool Earth Forum, December 2019, https://www.icef.go.jp/roadmap/

Process Electrification: *Process electrification is in the early stages of development and still faces challenges in meeting the high temperatures and heat transfer required in cement production. Direct and indirect calcination using electric heating have different challenges.*

For modern pre-calciner kilns, 40% of the fuel is fired in the kiln itself with flame temperatures reaching greater than 2,000°C. Clinkers, which form in a combination of viscous liquids and solids, coat the inside of the kiln, which protects the refractory. Attempts to produce Portland cement clinker in stationary (electric) vessels have often failed in the past because of the sticky nature of the clinker. Electrification is possible, but because the full reaction of the clinker currently takes place in the combination of liquid and solids, new methods face technological challenges.

Around 60% of the fuel is fired in the pre-calciner with temperatures reaching around 850–900°C. Not all kilns have pre-calciners, but all kilns built in roughly the last three decades have pre-calciners. Indirect calcination, which drives the calcination reaction through indirect heating, provides a fairly clean CO_2 stream from the calcination reaction (which accounts for more than half the emissions of a modern pre-calciner plant). Indirect heating can be performed in many fashions and many suggestions for indirect heating have been made, including using heating oils, indirect firing, electric induction coils, and even concentrating solar power. Indirect calcination would be relatively easy to design and incorporate in new cement plants and may be retrofitted (with a loss of thermal efficiency) in existing pre-calciner kiln systems.

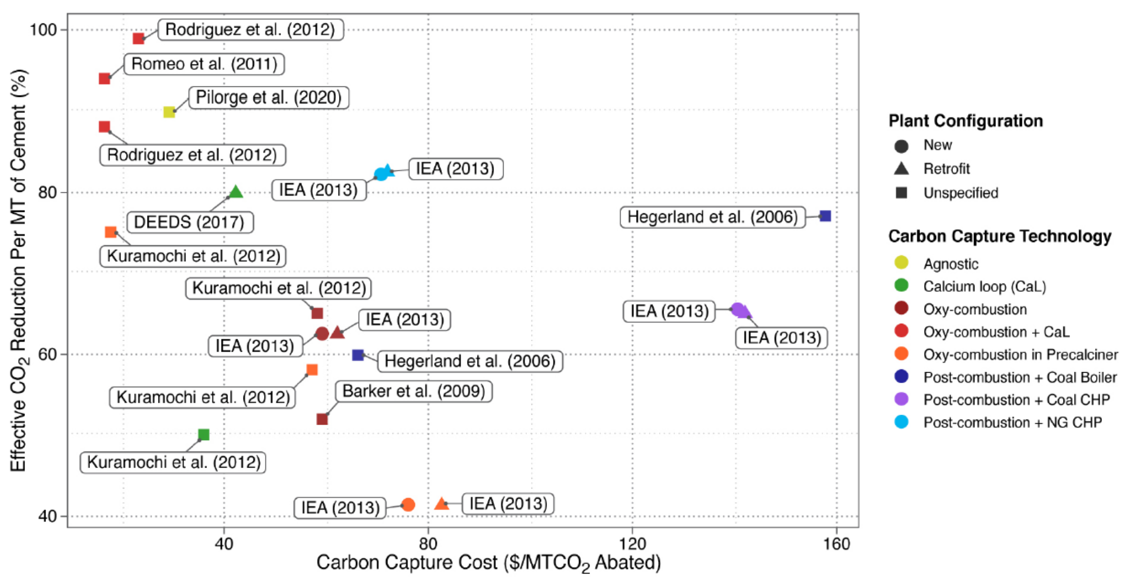
Though electric furnace technology for temperatures up to 1,000°C is in the early stages of commercialization for industrial-scale applications, much more RD&D is needed for higher temperatures. Given the aforementioned technological challenges, more basic RD&D is needed for electrification of the full kiln via plasma arc or other technologies. The use of electric heating for indirect calcination could also be studied in combination with CCUS, given the concentrated process CO_2 emissions associated with this route. Other electrification options also exist. Initial lab tests have shown that sintering of cement can occur at a lower temperature in a microwave environment and studies have investigated a hybrid method combining conventional kilns and an electric furnace that indicated lower energy use than the fully conventional route…

Hydrogen: *Hydrogen is another potentially transformative technology still in the research stage for application in cement kilns. Like other alternative fuels, using high levels of hydrogen in the fuel mix could affect physical aspects of the kiln such as the fuel mass flows, temperature profiles, heat transfer, exhaust gas moisture content, and safety considerations for the plant in ways that are not yet completely understood. Some of the challenges of utilizing hydrogen for cement kilns are around the properties of hydrogen, which require special handling and feeding and preclude use of pure hydrogen. For example, pure hydrogen flame has a lower heat transfer rate by radiation compared to natural gas which means the temperature profile of the kiln and the injection of the raw meal or clinker dust have to be modified. Another potential problem is acidification—as the gas is cooled, nitrogen oxides, sulfur oxides, and chlorine may form, and higher moisture content in the exhaust gases going to the main baghouse may cause damage. The potential impact on refractory from high levels of hydrogen in the fuel mix is still unknown. However, there is the possibility of using low proportions of hydrogen in the fuel mix without needing substantial changes in operation…*

4.1.5. Carbon Capture, Utilization, and Storage

Given that process-related CO_2 emissions from calcination accounted for 58% of total CO_2 emissions from the U.S. cement industry in 2015, the adoption of CCUS technologies is key to achieving decarbonization in this subsector. There are technological challenges to storing CO_2 near cement kilns, which are often co-located with large limestone quarries, and each plant has its own unique geography with varying amounts of land area, water, power infrastructure, and other resources. No single off-the-shelf CCUS commercial design or technology will work for every cement plant, given *the geographical variations and the varying emissions control technologies and designs at different plants. Transport infrastructure for CO_2 varies significantly from site to site. In addition, existing plants retrofitted for carbon capture and carbon capture integrated with new cement plants would have very different capture efficiencies.*

CCUS is currently a very high-cost technology for cement plants in terms of both capital and operating costs, including an energy penalty (figure below). Calcium looping and oxy-combustion capture appear to be more cost effective than post combustion capture, likely because about 60% of CO_2 from clinker production is process CO_2 that is present in higher in concentration than CO_2 as a combustion byproduct. Avoiding the mixing of the large fraction of high purity process CO_2 stream with the smaller fraction of lower CO_2 concentration flue gas from fuel combustion for calcination and clinkering – by using oxygen instead of air for combustion (to produce high CO_2 concentration flue gas) and or using inexpensive lime sorbents in a regenerative calcium looping process to extract high purity CO_2 ($CaO + CO_2 \rightleftharpoons CaCO_3$) – appears to preclude the need for more capital-intensive amine-based post combustion capture process, leading to a more cost-effective carbon capture approach. A thorough techno-economic and energy analysis across capture technologies with a consistent set of assumptions is needed to verify this hypothesis…



Estimates of cost of CO_2 avoided and corresponding effective CO_2 reduction rate using various carbon capture technologies in cement production as reported in literature.[15]

CaL = calcium loop; CHP = combined heat and power plant. Each data point contains built-in assumptions about a range of parameters including plant lifetime, capital charge factor, discount rate, capture rate, unit energy demands, and unit process conditions for a given capture technology, mix and carbon content of clinker feed, and cost components (E.G., CO_2 transportation). Calcium looping and oxy-combustion appear to generally be more cost effective than post-combustion carbon capture. However, in the absence of harmonization of these estimates across technologies and timeframes, we caution against direct quantitative comparison of cost values, including those for identical capture technologies. Figure source: this work.

[15] Note that there were many references for this chart. Please see reference 3, page 148 for full list.