Low-carbon Fuel Pathway to Decarbonize Hard to Electrify Industries. Case Study: Cement and Glass Industries

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ABSTRACT

Cement and glass are both vital to the world economy. These manufacturing industries are also energy intensive and produce significant carbon emissions. Decarbonization challenges include the historical dominance and low costs of fossil fuels. While possible potential decarbonization pathways using alternative fuels have been identified, they face significant barriers to widespread adoption, including technical challenges, availability, and cost. Though electrification is a pathway to decarbonize the industrial sector, there are some industries that are difficult to electrify. Cement and glass industries are an example of industry sectors that is difficult to decarbonize through electrification. The primary reason lies in the cement manufacturing process itself. Only about 45% of carbon dioxide emissions from cement manufacturing comes from fossil fuel combustion while the remaining 55% is a result of the chemical reduction process of clinker production that liberates CO_2. This paper identifies the challenges associated with electrification and the potential decarbonization strategies in these industries through the application of low carbon fuels and innovative cement materials. Research performed in this area to date suggests that measures to improve both electrical and thermal energy efficiency can lower carbon emissions in these industries. Among alternative fuel options for both industries, waste-derived fuels—created from tires, sawdust, waste oils, sludge, and other types of waste—are most promising because they are less expensive, offer a lower-carbon footprint, and are an effective method of waste management. These and other approaches employed by cement companies as well as research organizations around the world will be elaborated upon further in this paper.

Introduction

Cement is the key component in concrete, the most widely used building material worldwide. Figure 1 describes the cement manufacturing processes. The primary raw materials in cement production are limestone and clay, which are crushed to produce raw meal. The raw meal is preheated using hot exhaust gases from the downstream kiln to remove moisture and enhance process efficiency. The preheated raw meal is then moved to the pre-calciner above the kiln, where calcium carbonate (limestone) is converted to calcium oxide (lime). The CO_2 released by this process accounts for 55% of the cement manufacturing's total CO_2 emissions.[1] The pre-calcined meal is heated to more than 1652°F (900°C) in a rotary kiln, which is further

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[1] Ali Hasanbeigi, Ph.D., Global Efficiency Intelligence, "Global Cement Industry's GHG Emissions," May 17, 2021, https://www.globalefficiencyintel.com/new-blog/2021/global-cement-industry-ghg-emissions.

heated to 2732°F (1500°C). The emissions from fossil-fuel combustion to heat the rotary kiln accounts for 32% of the industry's CO_2 emissions.[2]

The high-temperature calcination forms nodules or lumps of clinker, which is an intermediary product in cement manufacturing. Coolers then reduce clinker temperature, which is essential for producing high-quality cement. Cooling the clinker also recaptures heat for combustion, which improves the system's overall thermal efficiency.

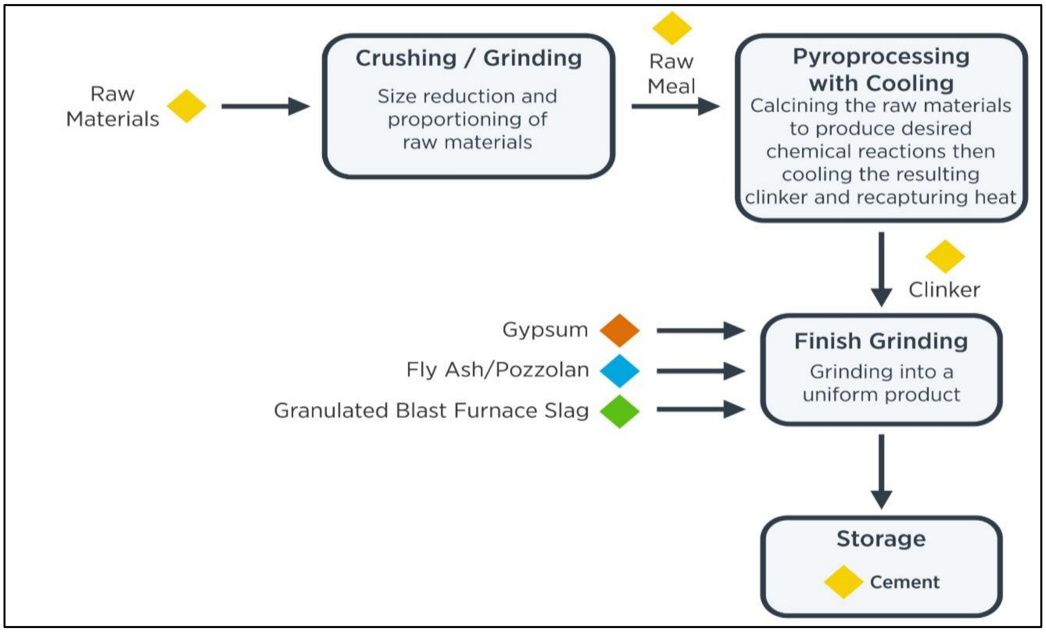

Figure 1. Cement manufacturing process flow diagram

The glass industry can be categorized into four sectors based on end-use application:

- Flat glass is used in building materials, automobile parts, solar equipment etc. About 45% of manufactured glass is flat glass.
- Container glass is used in packaging materials for the food and beverage industry, pharmaceuticals, cosmetics, and other packaging. About 33% of manufactured glass is container glass.
- Special glass is used in heat-resistant applications including ovenware, lighting and laboratory equipment, and test tubes. About 16% of manufactured glass is special glass.
- Glass fiber is used in insulation, optical fiber, and material reinforcement. About 6% of manufactured glass is glass fiber.

Broadly, glass production involves the following four steps (see Figure 2):[3]

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[2] Zero Carbon Australia, "Zero Carbon Industry Plan: Rethinking Cement," August 2017, https://bze.org.au/wp-content/uploads/2020/12/rethinking-cement-bze-report-2017.pdf.

[3] U.S. DOE, Office of Energy Efficiency & Renewable Energy, Advanced Manufacturing Office, "Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Glass Manufacturing," September 2017, https://www.energy.gov/sites/default/files/2019/05/f62/Glass_bandwidth_study_2017.pdf.

- Batch preparation and mixing
- Melting, refining and conditioning
- Forming
- Finishing

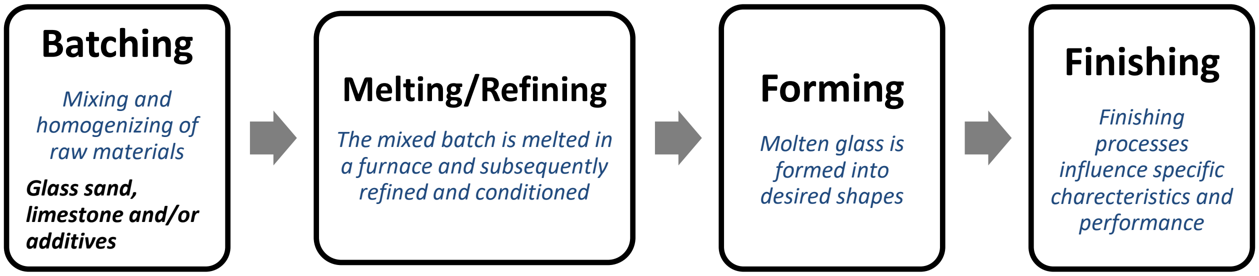

Figure 2. Glass manufacturing process flow diagram[4]

In the first step, raw materials are blended, ground, and mixed before transfer to a high-temperature melting furnace at 2552-3002°F (1400-1650°C). Next, the melted batch is refined and homogenized. In the third step, molten glass is formed into its final shape. Finally, shaped glass is finished to produce the final product.

Glass properties vary based on the raw materials used in production. Typical raw materials include silica/glass sand, magnesia, limestone, soda ash, alumina, potash, borosilicate, and other additives. Fluxes (e.g., soda ash or potash) are added to reduce the temperature at which the raw materials melt. Stabilizers (e.g., limestone or alumina) are added to enhance the chemical stability of the formed glass. Cullet or recycled glass may also be part of the raw material.

Emissions in the Cement and Glass Industries

The choice of raw materials affects emissions in both industries. In both cement and glass manufacturing, the incumbent raw materials used generate significant CO_2 emissions during processing. As shown in Figure 3, 55% of cement industry CO_2 emissions are process emissions. Substituting raw materials that emit less CO_2 during manufacturing can reduce overall emissions. In Figure 3, indirect emissions from grinding materials (13% of cement industry emissions) are electricity-related emissions.

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[4] U.S. DOE, Office of Energy Efficiency & Renewable Energy, Advanced Manufacturing Office, “Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Glass Manufacturing,” September 2017, https://www.energy.gov/sites/default/files/2019/05/f62/Glass_bandwidth_study_2017.pdf.

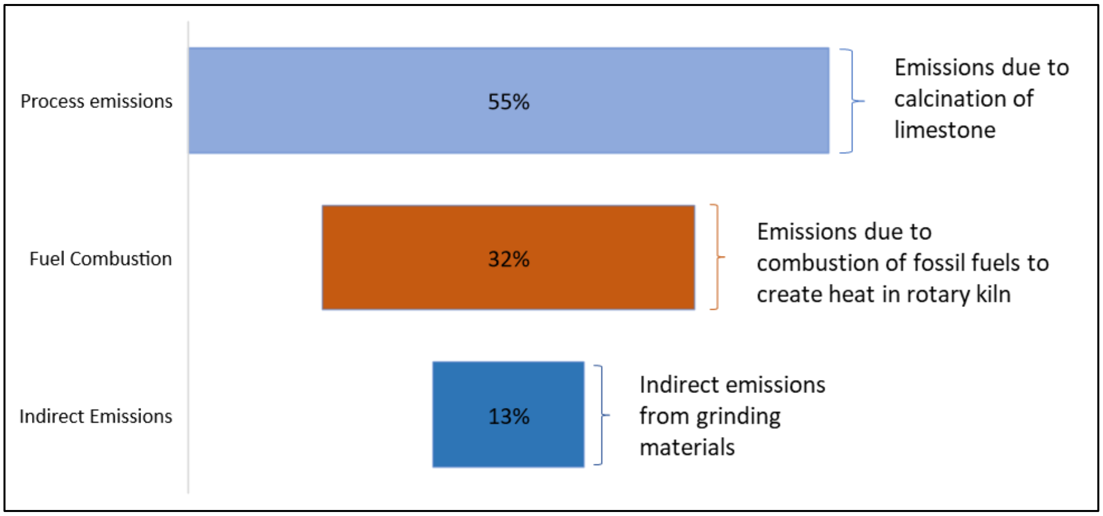

Figure 3. Greenhouse gas source emissions in cement production[5]

Different types of glass consume different amounts of energy and generate different amounts of emissions. Figure 4 shows 2010 CO_2 emissions by glass type.[6] Flat glass produces the most CO_2 emissions due to higher energy intensity.

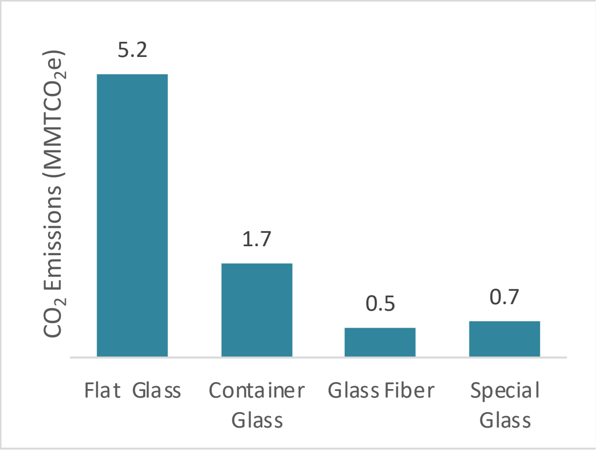

Figure 4. CO_2 Emissions by glass type in 2010[7]

Low Carbon Pathways in Cement and Glass Production

Both the cement and glass industries generate similar emissions:

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[5] Zero Carbon Australia, "Zero Carbon Industry Plan: Rethinking Cement," August 2017, https://bze.org.au/wp-content/uploads/2020/12/rethinking-cement-bze-report-2017.pdf. [repeated]

[6] U.S. DOE, Office of Energy Efficiency & Renewable Energy, Advanced Manufacturing Office, "Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Glass Manufacturing," September 2017, https://www.energy.gov/sites/default/files/2019/05/f62/Glass_bandwidth_study_2017.pdf. [repeated]

[7] U.S. DOE, Office of Energy Efficiency & Renewable Energy, Advanced Manufacturing Office, "Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Glass Manufacturing," September 2017, https://www.energy.gov/sites/default/files/2019/05/f62/Glass_bandwidth_study_2017.pdf. [repeated]

- Process-related emissions
- Fuel-combustion emissions
- Indirect emissions associated with electricity consumption

Because their emissions are similar, decarbonizing the cement and glass industries poses similar challenges and opportunities. The following decarbonization strategies have been commonly explored for both the cement and glass industries.

Energy Efficiency Improvements

Energy efficiency improvements can be facilitated through electrical energy efficiency and thermal energy efficiency. Electrical energy efficiency can be improved by replacing older technologies with modern technologies such as modern grinding machines, increased automation, and variable-speed drives. Thermal energy efficiency can be improved by replacing older wet kiln technology with dry kilns and implementing waste heat recovery systems. A challenge with increasing the overall energy efficiency is the large capital investment needed to switch to higher thermal and electrical efficiency systems and diminishing economic and environmental returns on those investments.

Recycling and Material Efficiency

Adding recycled glass or cullet during batch preparation is an effective way to reduce net energy consumption in glass manufacturing. Using cullet is an effective waste management method and conserves natural resources used to produce glass. Glass recycling can lower the carbon footprint because it generates no processing byproducts and reduces the amount of heat required for processing.

Demand-side emission mitigation strategies are being explored to optimize cement demand. Strategies include material-efficient design, performance-based concrete design, use of precast concrete components, post-tensioning, and avoidance of over-design. More intensive use of buildings and infrastructure, through means such as enhanced sharing practices and consolidation of urban functions, would reduce the need for additional building infrastructure. Building more robust structures and extending the service life of buildings and infrastructure, reducing construction waste, component reuse, downcycling, and stockpiling of demolition are other ways to enhance material efficiency.

Alternative Fuels

Clinker production requires temperatures of more than 2552°F (1400°C). The cement industry is exploring the possible use of carbon-neutral fuels (such as biomass and waste-derived fuels) to generate heat. An estimated 20-30% of fossil fuels can be replaced with biomass/biofuels without significant capital investments.[8] However, blending/substituting fossil fuels with biomass/biofuels can be technically challenging due to complex chemical kinetics and non-homogeneity in physical and chemical characteristics such as particle size, moisture, and ash contents.

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[8] R. T. Kusuma, et al., "Sustainable transition towards biomass-based cement industry: A review," *Renewable and Sustainable Energy Reviews*, v. 163, July 2022, https://www.sciencedirect.com/science/article/pii/S1364032122004075.

Carbon-neutral biomass-based fuels are another alternative fuel. As part of the Canadian Cement 2020 initiative, Lafarge Canada Inc. replaced 10% of its traditional fuel in an Ontario plant with fuels derived hemp, sorghum, willow, switchgrass, and oat hulls.[9]. Because biomass fuels are much more expensive than fossil fuels and waste-derived fuels, their use cost presents challenges.

Hydrogen is expected to become an important fuel in the industrial sector. U.S.-based cement manufacturer, CEMEX, has successfully deployed a cement plant in Europe that includes hydrogen as part of the fuel mix. Hydrogen offers a path to a low carbon cement production if produced using net zero carbon processes. Today, hydrogen used in the cement- and glass-manufacturing fuel mix is created from steam-reforming processes that use natural gas, methane, and coal. However, green hydrogen, which is generated using renewable electricity, could help lower even more emissions right from the source. It is important to note is that heat content of hydrogen is approximately 3 times lower than natural gas by volume, so more hydrogen is needed to produce the same amount of heat (Btu) needed in the kiln. This causes an issue related to the infrastructure costs, land area, and right-of-way requirements for transport and storage of hydrogen and for the green electrical power supply. Furthermore, combustion control and flame management are more difficult with hydrogen than with natural gas resulting in burner designs for hydrogen having mor complex engineering constraints than that of natural gas. These are some of the technical challenges that are still being evaluated in various ongoing research projects.

Combining alternative fuels is another possible decarbonization pathway. The British company Heidelberg Cement used both hydrogen and biomass fuels to deploy a cement kiln with 100% carbon-neutral fuels in a fuel mix of 39% hydrogen, 12% meat and bone meal, and 49% glycerin.

When considering direct electrification of the process het inputs, sourcing electricity from renewable resources is also a feasible option, and use of solar thermal energy in cement kilns is an option being studied. CEMEX partnered with Swiss company Synhelion SA to pilot a cement kiln powered by concentrated solar thermal energy. In the pilot plant located in Spain, solar towers were used to concentrate solar radiation to reach a temperature of 2732°F (1500°C).[10] Finally, oxyfuel combustion is a potential enabling measure addressing fuel combustion-related emissions. This mode of combustion takes place in an oxygen-rich environment that concentrates CO_2 emissions, making them easier to capture. Despite concerns that changing atmosphere in the kiln would impact clinker quality, early research shows cement properties may remain unchanged.[11] An alternative to direct electrification from the grid is the emerging concept of implementing small modular nuclear reactors to support energy intense industries. Conceptually this approach could provide base load electric power to the site with any excess power being available to the grid. Conversely, the grid then offers a back-up energy source for the nuclear power. If low overall cost/price target of delivered power can be achieved, then this could support direct or inductive electrified heating alternatives. Furthermore, indirect thermal coupling of nuclear power for industrial heat is being investigated wherein thermal energy

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[9] P. S. Fennell, et al., "Decarbonizing cement production," *Joule*, v. 5, no. 6, pp 1305-1311, June 2021, https://www.sciencedirect.com/science/article/pii/S2542435121001975.

[10] CEMEX, "CEMEX and Synhelion achieve breakthrough in cement production with solar energy," February 2, 2022, https://www.cemex.com/-/cemex-and-synhelion-achieve-breakthrough-in-cement-production-with-solar-energy.

[11] The European Cement Association, "The role of Cement in the 2050 Low Carbon Economy," undated, https://cembureau.eu/media/cpvoin5t/cembureau_2050roadmap_lowcarboneconomy_2013-09-01.pdf.

storage and heat quality upgrading could be applied. However, reaching the temperatures required in calcination and clinker production are currently outside of the capability of concepts under development and therefore indirect thermal inputs would only serve in a pre-heat capacity and only partially offsetting plant fossil fuel demand.

Like cement, glass production requires process temperatures greater than 2552°F (1400°C). Research and development are underway to explore the use of alternative fuels for the glass industry, including low-carbon hydrogen, as well as electrification of kilns and melting furnaces, microwaves, and plasma furnaces. Electric furnaces, that offer greater thermal efficiencies than traditional furnaces, are also being researched. By eliminating or reducing the need for natural gas pipelines and traditional furnace components, electrification may also potentially reduce capital costs.

In both industries, all-electric heating—including resistance, microwave and plasma furnace concepts—offers competitive alternatives for process heat. While their final energy efficiency may be greater than other combustible-fuel options, the cost to transmit, deliver, and store sufficient electric power generated from low-carbon sources may significantly offset these efficiency advantages.

For both industries, each type of alternative fuel requires significant investment in grid-side and on-site infrastructure, the costs of which would be borne by the manufacturers. First-mover risks in these highly competitive commodity industries are perceived to be large.

Carbon Capture and Sequestration (CCUS)

Carbon capture use and sequestration is a promising method to decarbonize cement and glass industries because it is effective for both process and fuel-combustion emissions. The CO_2 generated from cement and glass production can be compressed or liquified, transported, and permanently sequestered or stored for use in other industries such as beverages or synthetic fuel production.

CCUS advancements through various capture technologies are a promising research topic in the cement industry. These include a variety of solvent, sorbent, and membrane technologies including carbonation, mineralization, calcium (or carbonate looping), and algae capture.

A recent EPRI study focuses on CCUS in non-power industries including cement and glass manufacturing, which is a growing area of focus for CCUS implementation. These include cost metrics (especially in the context of industrial plants with multiple output products), energy supply aspects, retrofitting costs, maturity of the capture technology, and CO_2 transport and storage costs. The study delivers recommendations to better include and address these issues in cost evaluations for industrial applications. In general, it finds that CCUS may be economically viable at a utility scale but faces economic challenges when downward scaling for industrial applications. However, because of the highly concentrated and relatively pure process emissions associated with concrete and glass production and the potential to oxy-fire for combustion of fossil or carbon based waste fuels offering a more highly concentrated CO2 stream from combustion, this approach may prove cost competitive at this smaller scale. Furthermore, the opportunity to use these pure CO2 streams as a feedstock for e-fuel production (e.g. Sustainable Aviation Fuel) offers the potential for an additional net economy CO2 emissions production. When accounting for this carbon reduction and the value of the CO2 as a feedstock the business cause would be further enhanced.

Use of Low-Carbon Raw Material in the Cement Industry

The main raw material used in cement production has traditionally been limestone. Substituting limestone and other carbonated raw materials that contain no carbon would reduce the process emissions. The cement industry already replaces some of its raw materials with waste and by-products from other industrial processes such as calcium, silica, alumina and iron. These can be used as raw materials in the kiln, replacing natural substances such as clay, shale, and limestone. Ashes from lignite or coal, blast furnace slag, concrete crusher sand, and aerated concrete meal that have already been decarbonated could be used as an alternative to limestone by avoiding CO_2 emissions during its transformation to lime in the production process. Challenges in using low-carbon raw material include the presence of silica, alumina, magnesium, or sulfur in high concentrations, which can hinder large-scale use of alternative decarbonated raw materials since they may impact the durability and the strength of the concrete. In addition, the presence of volatile organic compounds (VOCs), trace elements content, or variable compositions may in some cases result in environmental restrictions under other regulations such as limits on criteria air pollutants. Moreover, the continued availability of such decarbonated raw materials, especially those that arise as process byproducts from other industries can be limited.

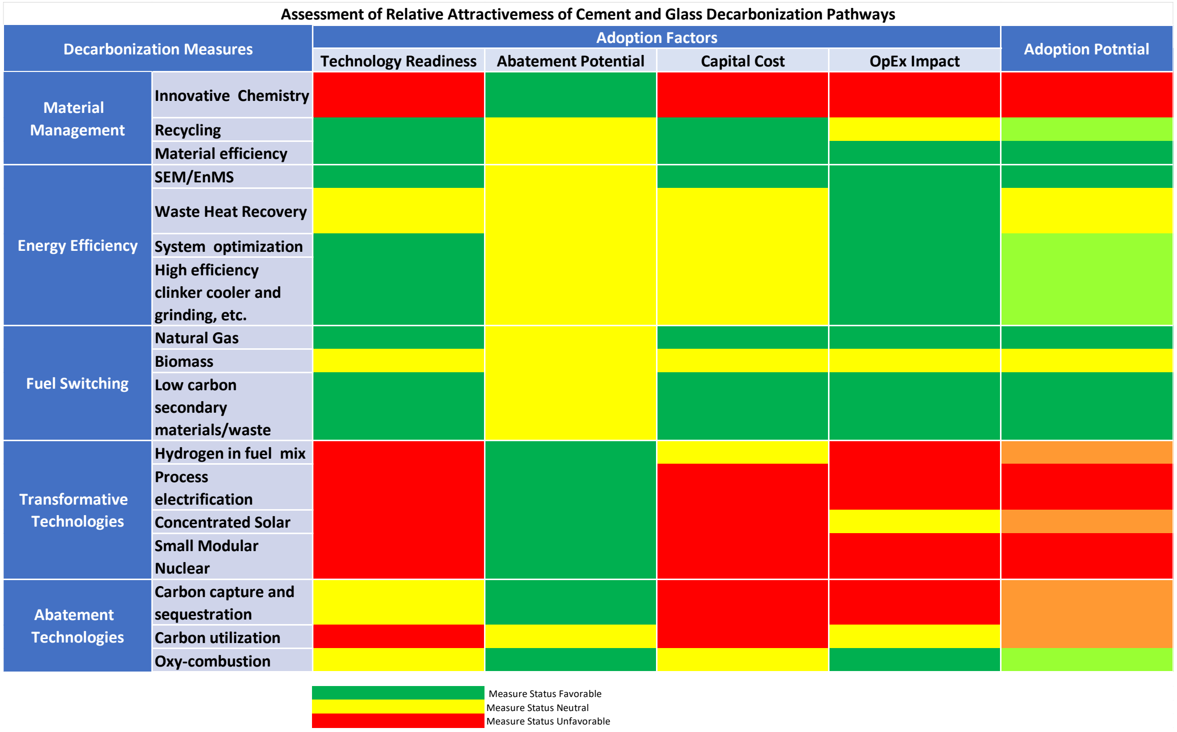
Clinker Substitution and Novel Cements

Clinker substitution offsets carbon emissions by adding lower-carbon raw materials to the clinker production process. Alternative materials include fly ash, slag, silica fume, and pozzolans such as clay and shale are also used in clinker substitution. A new process under development is based on a sulfur-reduction cycle relies on plentiful basalt as the primary cementitious-material feedstock. When used with renewable energy sources, these technologies offer the potential of carbon-free or possibly carbon-negative lifecycle concrete for the construction industry.

In addition to using new feedstocks, novel cements can be created using new production processes. Because the setting times of novel cement are different from those of traditional cement, market acceptance may present a challenge. Large-scale adoption of clinker substitution and novel cements is hampered by a lack of existing regulatory standards, which in turn need to be substantiated with long-term research and testing.

Analysis and Discussion

Following the pillars of industrial decarbonization outlined by the DOE in a rigorous collaborative peer process the cement and glass industries are faced with the alternatives shown as the major Decarbonization categories in Figure 5. This assessment attempts to classify important factors that will impact the attractiveness of the technology for potential adoption. In this regard it is possible to qualitatively classify measures as favored, neutral or disfavored for adoption. While this exercise makes no attempt to apply a weighting to these adoption factors it is reasonable to assume that for each pillar some factors will be less influential on the conversion decision by industry players. From the perspective of **Technology Readiness** of the technology areas listed a classification of “Favored” implies that the technology is commercially available today, “Disfavored” would refer to technologies that have not reached a-scale demonstration and a “Neutral” classification would refer to a technology in late stage demonstration with manufacturing processes and supply chains under development. Looking at **Abatement Potential** an unfavorable attractiveness would be associated with a technology that can only partially offset CO2 emissions of only one of the major contributing sources (process or combustion) or only relates to Scope II emissions. For this factor a designation of favorable attractiveness would assume that the technology has the potential to entirely offset either the process or fuel combustion emissions or a majority of the combined emissions with limited Scope II impacts in the long run. Technologies designates as having a neutral attractiveness have the potential to offset significant CO2 emissions on an aggregate basis but do not reach the level of a technology that can abate the majority of either process or combustion emissions. When considering **Capital Cost** and **OpEx Impacts** we generally think in terms of a technology's likely impact on the total cost of production within a +/- 10 % range. So, if the magnitude of impacts of the weighted average cost of invested capital or impacts on operating expense are likely to increase the unit cost of production by 10% or more we rate those technologies as disfavored. Similarly, if there is an anticipated favorable return on capital or reduction in operating expense that could reduce net cost of production by 10% then the measure would achieve a favorable rating with a neutral rating for technologies expected to have minimal net cost of production impacts.



Assessment of Relative Attractivemess of Cement and Glass Decarbonization Pathways

Decarbonization Measures		Adoption Factors				Adoption Potntial
		Technology Readiness	Abatement Potential	Capital Cost	OpEx Impact	
Material Management	Innovative Chemistry	🟥	🟩	🟥	🟥	🟥
	Recycling	🟩	🟨	🟩	🟨	🟢
	Material efficiency	🟩	🟨	🟩	🟩	🟩
Energy Efficiency	SEM/EnMS	🟩	🟨	🟩	🟩	🟩
	Waste Heat Recovery	🟨	🟨	🟨	🟩	🟨
	System optimization	🟩	🟨	🟨	🟩	🟢
	High efficiency clinker cooler and grinding, etc.	🟩	🟨	🟨	🟩	🟢
Fuel Switching	Natural Gas	🟩	🟨	🟩	🟩	🟩
	Biomass	🟨	🟨	🟨	🟨	🟨
	Low carbon secondary materials/waste	🟩	🟨	🟩	🟩	🟩
Transformative Technologies	Hydrogen in fuel mix	🟥	🟩	🟨	🟥	🟧
	Process electrification	🟥	🟩	🟥	🟥	🟥
	Concentrated Solar	🟥	🟩	🟥	🟨	🟧
	Small Modular Nuclear	🟥	🟩	🟥	🟥	🟥
Abatement Technologies	Carbon capture and sequestration	🟨	🟩	🟥	🟥	🟧
	Carbon utilization	🟥	🟨	🟥	🟨	🟧
	Oxy-combustion	🟨	🟩	🟨	🟩	🟢

🟩 Measure Status Favorable
🟨 Measure Status Neutral
🟥 Measure Status Unfavorable

Figure 5 CO_2 Abatement Measure Attractiveness

Based on the analysis above efficiency measures associated with materials management and incumbent final energy usage are generally favored as is strategic fuel switching options for combustion-based process heating. It is worth noting however that all of these decarbonization pathways are expected to have a somewhat limited impact on overall industry aggregate CO_2 emissions. This is primarily due to the fact that individually each will only trim single to low double-digit percentages of the carbon footprint and only with regard to the fuel combustion piece of the emissions pie. If applied in tandem these technologies could abate a significant portion of the overall emissions from fossil fuel combustion for process heat however abatement of a majority of the fuel demand and attendant CO_2 emissions is not likely due to the enormous thermal lift required to initiate and sustain the chemical reactions involved.

In the Materials space the complete redesign of cement and its production are contemplated that would involve the creation of an entirely new raw materials supply chain, new process technologies currently unproven at scale, and potentially new sources of primary energy currently in mid to late-stage demonstration. While the potential to completely eliminate process emissions and dramatically reduce Scope I and II process heat related emissions exists these technologies are not expected to emerge in a timeframe to significantly impact the mid-century net-zero carbon goals.

This is roughly a similar case with the other Transformative Technologies and CCUS options evaluated. While all these pathways exhibit the potential to completely eliminate large portions of the cement and glass industries' respective carbon footprints, none are at a readiness level that approaches commercial viability. Some are closer than others with sub-scale demonstrations either planned or underway, but the manufacturing and supply chain readiness to begin transforming a market to these concepts are years away and will only develop as economic viability can be attained. Of particular interest in these industries is the prospect for hydrogen or some other green hydrogen base syn-fuel that mimics natural gas in availability, thermal and flame characteristics ant thermal performance to emerge at something approaching price parity with incumbent fossil fuels. This attractiveness of this option has at its heart the potential to convert existing process at relatively low capital cost, with minimal interruption of operations and with limited impacts on thermal efficiency and productivity. Burner design and testing are underway along with evaluation of the impacts on and cost of ancillary systems upgrades that would be needed to blend high percentages of hydrogen, up to 100% as a process heating fuel. Other impacts on products and process would still need to be modeled and tested and there would need to be a significant reduction in the expected price of green hydrogen for this pathway to achieve commercial viability.

Lastly, we can address the pathways of CCUS to gain favor in the industry. As previously discussed, carbon capture technologies currently available do not scale downward well into smaller units appropriate to the industrial space. However, for glass and concrete the presence of a dominant process CO_2 emissions stream with few near-term alternatives to address, carbon capture scenarios must be given serious consideration. Large scale systems are in demonstration mode and there are a variety of potential carbon capture technologies emerging from late-stage development that could be applied to the rich CO_2 effluent streams associated with cement and glass production. Furthermore, were oxy-firing technologies to be applied to the process heating combustion systems then a much more concentrated CO_2 stream could also be presented to the carbon capture system from that source. These attributes increase the relative efficiency of carbon capture and potentially reduce the CapEx and OpEx requirements of the overall system. As research continues this pathway and these costs begin to com in line with feasible target for the industry the only question that remains is what to do with the captured CO_2. If the site has the luxury of being near a viable geologic sequestration field, then that might be the obvious and most attractive solution for those facilities. However, on site storage, compression, and transport of CO_2 to viable sequestration fields may be "out of the money" for sites not so conveniently located. In those instances, finding an attractive nearby end use for CO_2 as a feedstock for other processes that are inherently sustainable may be the most attractive option. Candidates for CCU include concrete curing, production of chemical building blocks for polymers and other hydrocarbon compounds, and the production of synthetic fuels for the mobility sector where the high energy density of liquid fuels is paramount.

Summary and Conclusions

The cement and glass industries generate significant CO_2 emissions from fuel combustion and industrial processes. Decarbonization challenges in these industries includes the historical dominance and low costs of fossil fuels. While possible alternative fuels have been identified, they face significant barriers to adoption, including technical challenges, availability, and cost. This report reviewed incumbent fuels, process flows, and emissions sources in these industries and explored potential low-carbon pathways to reduce emissions.

In both industries, using carbon-neutral biofuels and waste-derived fuels is a short-term strategy to reduce emissions. However, availability and competition for these fuel sources may present challenges. Carbon capture and sequestration is another long-term strategy that should be explored to decarbonize the cement and glass industries. Waste-heat recovery systems can heat buildings and districts with heat from industrial processes that would otherwise be lost.
In the cement industry, clinker substitution in which limestone is blended with low-carbon source materials (such as fly ash and slag) is gaining traction commercially. A mid- to long-term cement decarbonization strategy includes exploring zero-carbon fuel such as green hydrogen and maximizing advanced waste-to-heat-recovery techniques.

In the glass industry, increasing the amount of recycled glass or cullet in the raw material mix would reduce glass production’s carbon footprint.