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Chemicals Practice

Laying the foundation for zero-carbon cement

The cement industry is a top source of CO_2 emissions, but abatement pressures could prompt efforts to reimagine the business.

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May 2020

As a key component of concrete, cement is an integral part of our everyday lives. In fact, it is the second-most consumed product globally after potable water, and it is used in almost everything we build—from houses and cityscapes to dikes and dams. At the same time, it is also a major contributor to global CO_2 emissions.

Scientists and governments alike have called for increasingly stringent greenhouse gas (GHG) emissions targets as the consequences of climate change become more apparent. Recently, the goalpost has shifted from keeping the temperature rise below 2.0 degrees Celsius to 1.5 degrees Celsius, with more than 77[1] countries committed to net-zero emissions by 2050. Adding to pressures on the industry is the COVID-19 pandemic, which has hit the industry hard, undercutting demand with uncertainty around how deep the downturn will be and how long a recovery will take.

While it's unclear how the climate debate will unfold, reaching such goals by 2050 will be especially challenging for the cement industry, as most of its CO_2 emissions result from the unavoidable chemical process known as calcination. Unlike other industries that may be further along, the development of new technologies to decarbonize cement might not be scalable for years. Nonetheless, our research suggests that, in principle, the industry could reduce its 2017-level emissions by more than three-quarters by 2050.

Given its performance characteristics and the broad availability of limestone, cement (and therefore concrete) is likely to remain the construction material of choice globally. At a local level, however, it could lose share to more sustainable alternative materials, such as cross-laminated timber (CLT). Other shifts, including increased building-information modeling (BIM) and modular construction, could further reduce cement consumption, effectively shrinking demand, despite an overall increase in construction activity. Growth and decarbonization therefore represent significant, interrelated challenges. Paradoxically, perhaps, COVID-19 could accelerate the industry's response to these fundamental structural trends. As players address the challenges of uncertain demand, they have an opportunity to reset strategies: identifying the best path toward decarbonization, assessing digital and technological advancements to invest in, and rethinking their products, portfolios, partnerships, and construction methodologies—areas we explore later. Forward-thinking players could have an opportunity to leapfrog and become the industry front-runners.

Climate change and the cement industry: A baseline

The cement industry alone is responsible for about a quarter of all industry CO_2 emissions, and it also generates the most CO_2 emissions per dollar of revenue (Exhibit 1). About two-thirds of those total emissions result from calcination, the chemical reaction that occurs when raw materials such as limestone are exposed to high temperatures.

Cement acts as the binder between aggregates (fine and coarse rocks) in the formation of concrete. While cement makes up only a small percentage of the mix (approximately 12 percent by volume), it is almost exclusively responsible for the resulting CO_2 emissions. In the cement-manufacturing process, raw materials are heated to high temperatures in a kiln in a fuel-intensive process known as pyroprocessing (Exhibit 2). This results in clinker, small lumps of stony residue that are ground to a powder and combined with other ingredients to produce cement.

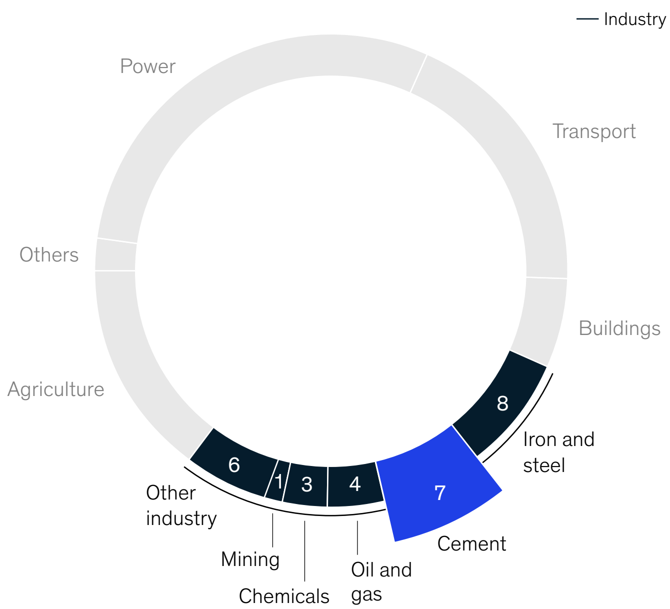
Pressure for the cement industry to decarbonize has increased rapidly, not only from society but also investors and governments. In fact, governments are now increasingly asking for environmental impact assessments before deciding whether to commit funding. As public scrutiny of CO_2 emissions increases, the risk remains that cement players could be "shamed" similar to oil and gas or mining companies in the past.

[1] Elena Kosolapova, "77 countries, 100+ cities commit to net zero carbon emissions by 2050 at climate summit," International Institute for Sustainable Development, September 14, 2019, sdg.iisd.org.

Exhibit 1

Cement production is a major source of global CO_2 emissions and also generates the most emissions per revenue dollar.

Share of global CO_2 emissions, % in 2017



kg of CO_2 per $

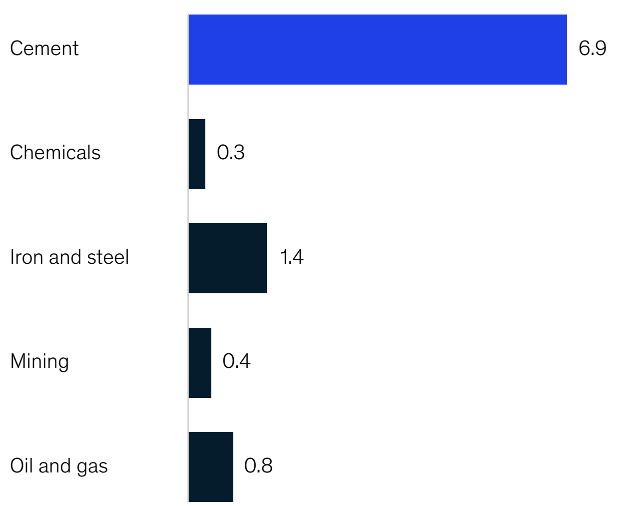
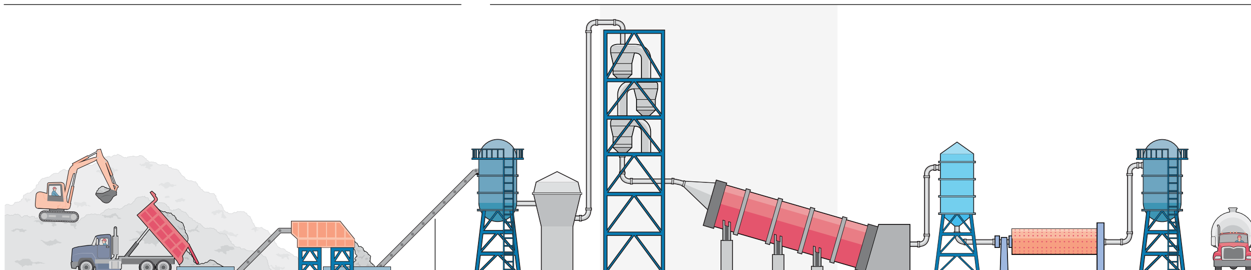


Exhibit 2

Cement manufacturing is a highly complex process.

Raw materials, energy, and resources | **Clinker and cement manufacturing**



	Quarry	Crusher	Transport[1]	Raw mill	Kiln and preheater/ precalcinator[2]	Cooler[3]	Cement mill	Logistics[4]	**Total**
Energy, megajoule/ton	40	5	40	100	3,150	160	285	115	3,895
CO_2, kilogram/ton	3	1	7	17	479 Calcination process; 319 Fossil fuels	28	49	22	925

[1]Assumed with 1kWh/t/100m.
[2]Assumed global average, data from the Global Cement and Concrete Association, Getting the Numbers Right 2017.
[3]Assumed reciprocating grate cooler with 5kWh/t clinker.
[4]Assumed lorry transportation for average 200km.

Potential decarbonization pathways

Companies have several options to decarbonize cement. Optimistically, our analyses show that CO_2 emissions could be reduced by 75 percent by 2050 (Exhibit 3). However, only a small portion (around 20 percent) will come from operational advances, while the remainder will need to come from technological innovation and new growth horizons.

Operational advances, such as energy-efficiency measures, have already largely been implemented, and the emissions-reduction potential from alternative fuels and clinker substitution is limited by the decreasing availability of input materials. More innovative approaches, such as new technologies and alternative building materials, will therefore be indispensable to achieve carbon-reduction targets by 2050. That said, the most promising levers, in terms of emissions-reduction potential, are still in development and have only been piloted or implemented on a small scale.

As the development of technologies such as carbon capture, use, and storage (CCUS) and carbon-cured concrete could take up to ten years, investments should be made as soon as possible. Our abatement cost curve (Exhibit 4) estimates the costs of several large-scale investments to reduce one ton of CO_2 (based on assumed future costs, CO_2 prices, and abatement volumes). A negative abatement cost—

Exhibit 3

The cement industry could cut three-quarters of its CO_2 emissions by 2050.[1]

Potential CO_2 emissions and reductions,[2] $GtCO_2$ anually

[1] Figures are global estimates for emissions potential, taking all potential levers into consideration.
[2] Effect might be smaller or larger depending on speed of shift.
[3] For example, carbon capture, use, and storage; carbon-cured concrete; 3-D printing.
[4] For example, cross-laminated timber, lean design, prefabricated/modular construction, building information modeling.
[5] Alternative building materials and other approaches will likely play an important role in decarbonizing the cement industry, but a great deal of uncertainty remains as to how much they will reduce emissions.

Source: "Getting the numbers right," Global Cement and Concrete Association, 2017, gccassociation.org; *Global Cement*, fifth edition, Freedonia Group, May 2019, freedoniagroup.com; *The Global Cement Report*, 13th edition, CemNet, cemnet.com; Umweltbundesamt (German Environment Agency); McKinsey 1.5-degree-pathway model; McKinsey Cement Demand Forecast Model such as for clinker substitutes—implies a benefit to the producer rather than a reduction in cost.

Abatement costs indicate ranges, as the exact price of goods depend on regional and future availability. For example, as the steel and energy sectors step up their decarbonization efforts, the availability of clinker substitutes such as pulverized fuel ash (fly ash) and granulated slag will decrease. The same holds true for biomass, which is likely to experience rising demand from other industries.

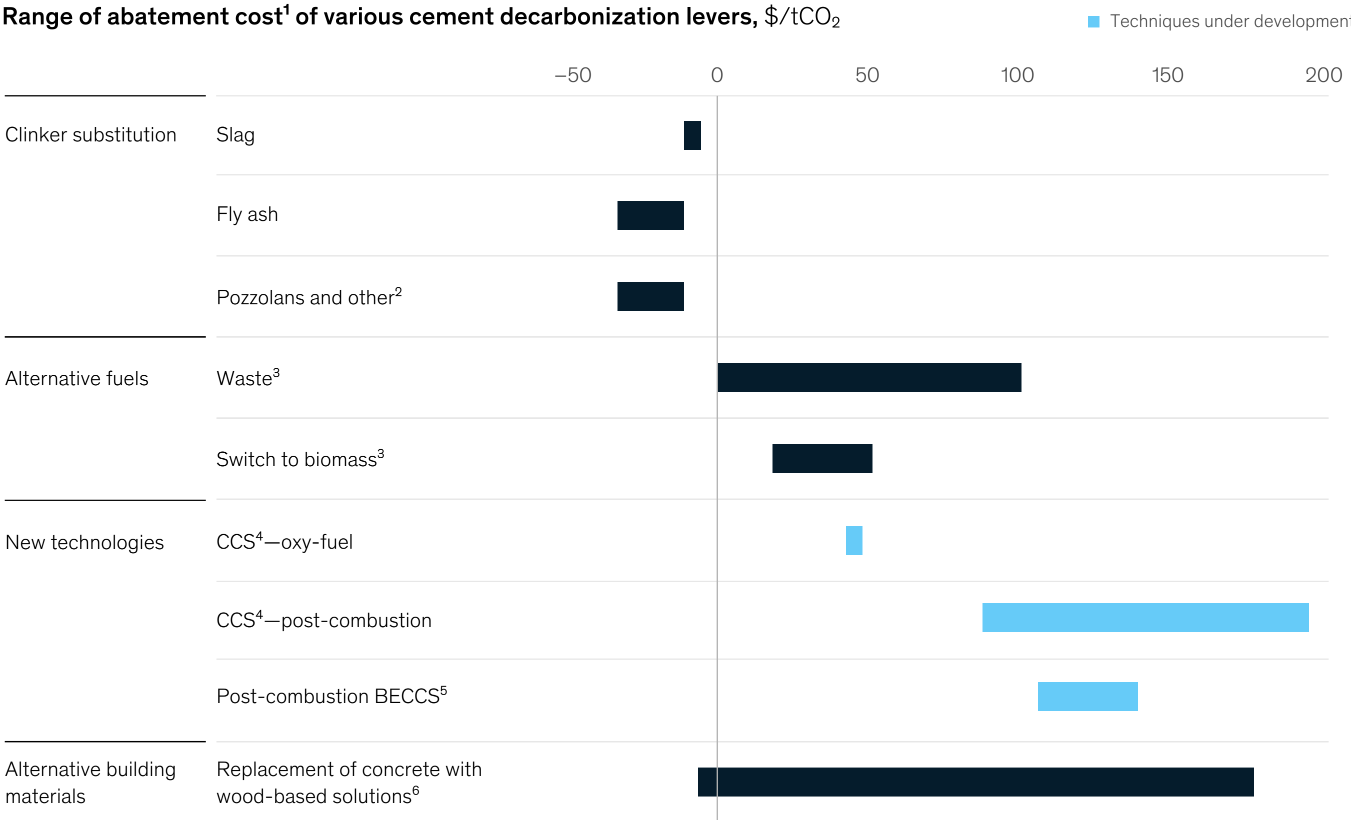
With the abatement costs of certain levers higher than CO_2 prices, cement manufacturers are faced with a dilemma: there is pressure from the public and financial investors to abate quickly, even though there is no economic rationale to do so. Not only do the economics seem far from stellar, but the required investment needs to be directed toward cost-reduction measures for cement producers to maintain their value share in the broader construction industry.

Overall, the future CO_2 emissions in 2050 are expected to be in line with global demand, slightly increasing to 2.9 $GtCO_2$ (Exhibit 5). Region-specific differences will persist, and the potential to reduce them will vary across regions because of country-specific regulatory approaches, different consumption needs, and the varying

Exhibit 4

Decarbonizing cement requires large-scale investments in technologies, bringing down both fuel and process emissions.

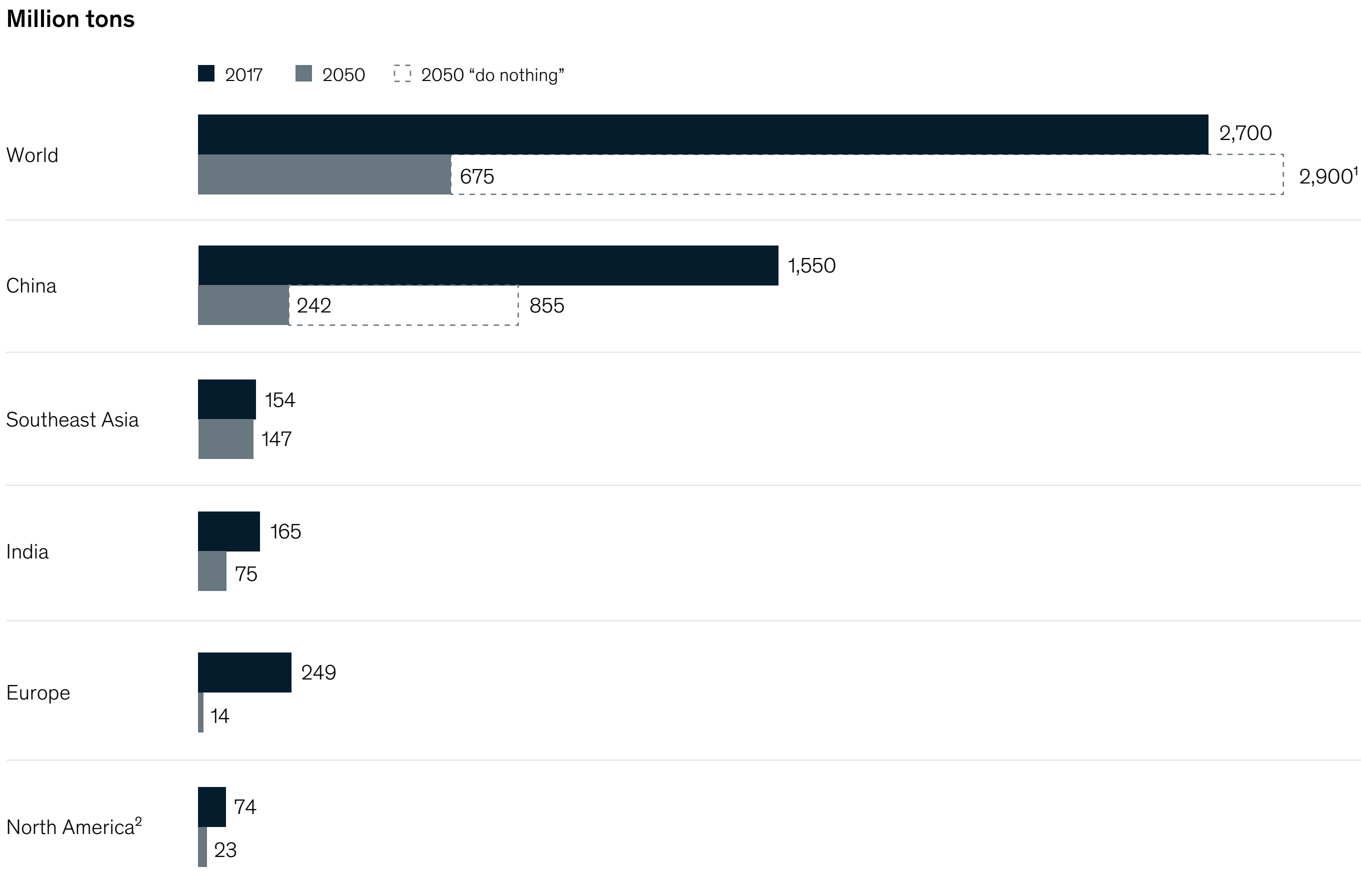
Range of abatement cost[1] of various cement decarbonization levers, $/$tCO_2$



[1] Globally assumed cost, can vary locally.
[2] Limestone, kaolin, and other.
[3] Depending on availability, quality of material, and cost to dispose.
[4] Carbon capture and storage.
[5] Bioenergy with carbon capture and storage.
[6] Includes abatement coming from displacement from steel.

Exhibit 5

CO_2 emissions are expected to decline worldwide compared with the 2050 'do nothing' scenario as traditional and innovation levers can be exploited and further developed.



[1] Overall demand is expected to increase slightly, though it will vary by region.
[2] Excluding Mexico.
Source: Global Cement and Concrete Association, Getting the Numbers Right Database; International Cement Review; McKinsey Cement Demand Forecast Model

levels at which local industries implement decarbonization measures.

For instance, China will benefit from a decline in demand (of about 45 percent) and should be expected to deploy both operational advances and technological innovation to decarbonize in the coming decades. Southeast Asia and India have started developing policies to promote decarbonization efforts. In 2012, the Indian government introduced a market-based mechanism to improve energy efficiency in which more than 85 cement plants participate. However, urbanization and economic development in these regions as well as the associated increase in demand may offset these efforts.

Investor scrutiny and regulatory pressure to reduce carbon emissions in the European and North American markets are likely to intensify. The European Union's ambitious Green Deal and its exhaustive package of measures, including the introduction of a carbon border–adjustment mechanism for cement, could reduce carbon emissions across the entire region. In North America, decarbonization efforts are promoted

A deep dive into decarbonization levers

Energy efficiency. The best way to improve energy efficiency is to focus on kilns, as they constitute around 90 percent of the total energy consumption. Industry-wide advancements in the 1980s helped lower energy emissions by shifting from burning wet raw material to dried raw material. Today, advanced analytics can process data and create adaptive, self-learning models. Such investments are typically recouped within one to two years.

Alternative fuels. A shift to less carbon-intensive alternative fuels, such as waste and biomass, for heating kilns could decrease direct CO_2 emissions from global cement production by 9 percent by 2050. However, the feasibility of this shift depends on the availability of alternative fuels as well as the development of local supply chains. While fossil fuels still deliver most of the energy consumed by the cement industry, about four times more biomass was used in 2017 than in 2000.

Clinker substitution. CO_2 emissions are directly proportionate to the amount of clinker used in cement production. Therefore, clinker can be substituted by cementitious materials such as natural and calcined pozzolans, as well as industrial byproducts such as fly ash and blast furnace slag. Similarly, the use of pozzolans depends on their availability, as natural reserves are limited to specific regions.

Carbon capture, use, and storage. This method isolates and collects CO_2 from industrial emissions and either recycles it for further industrial use or safely stores it underground. Once captured, a wide variety of potential uses for CO_2 could be possible, such as in the production of glass, plastics, or synthetic fuels. Though carbon-capture technologies do exist commercially, they are utilized in very few plants—one example being natural-gas plants. Therefore, the progress of extensive decarbonization will not only depend on the economic viability of storing and sequestering the carbon but also on the availability of CO_2 marketplaces, through which the captured CO_2 can be sold.

Carbon-cured concrete. This technology injects CO_2 captured during cement production to accelerate the curing process and "lock in" CO_2 in the end product. Current low-carbon cement technologies can sequester up to 5 percent of CO_2, with the potential of 30 percent. In fact, 60 million tons of CO_2 per year are projected to be stored via carbon-cured concrete in 2050.

Alternative building materials and other approaches. In the years to come, alternative building materials could shift demand away from cement. To date, cross-laminated timber (CLT) has attracted the most attention. Made by gluing wooden panels and boards together, CLT is an adequately fire-resistant building material that can reach large dimensions. Its application has recently increased and includes projects in Canada, Japan, and Sweden. Assuming a 10 percent replacement of concrete—and considering the CO_2 captured in the wood has been abated—would reduce the overall cement footprint by 25 percent, as even more CO_2 is captured than avoided by reducing the cement production. However, the annual net increment required would be about 700 million cubic meters, about 80 percent of the recognized supply of forest in Russia.

Other approaches include prefab, modular, and kit homes as well as building-information modeling. This last approach allows products to be visualized digitally, various building materials to be evaluated, and large projects to be planned more efficiently.

through state- and countrywide initiatives, such as Canada's 2019 implementation of the Carbon Pricing Backstop program.

The next normal: Reimagining the cement industry

Decarbonizing the cement industry requires two strategic challenges to be addressed. First, companies will need to identify the best paths toward decarbonization through operational advances and technological innovation as well as new growth horizons. Second, they will need to develop a portfolio for a new growth horizon that leverages opportunities across the "sustainable construction" value chain.

Operational advances

Building on decades of efforts to improve efficiency, traditional abatement levers could reduce emissions by about one-fifth by 2050. The industry could achieve this reduction by deploying more clinker substitutes, reducing energy intensity through better plant utilization, and increasing equipment effectiveness. Recovering waste heat (a by-product of machines or processes that use energy) could also provide carbon-free electricity.

Another efficiency lever is advanced analytics. One European cement producer achieved 6 percent fuel savings by creating self-learning models of a kiln's heat profile and optimizing the shape and intensity of the kiln flame. Future cement plants could leapfrog competitors by combining digital technology and more sustainable operations. Finally, incorporating alternative fuels such as waste and biomass to replace fossil fuels, a multidecade trend in the industry, could reduce emissions by nearly 10 percent by 2050.[2]

None of this will be easy. Biomass supply varies by region, and other industries are vying for them. Clinker substitutes, too, are limited. Natural pozzolans (for example, volcanic rock and ash) have not yet been assessed at scale. And industrial byproducts that serve as clinker alternatives, such as fly ash from coal-fired power plants and slag from steel-blast furnaces, could be in shorter supply as the power and steel industries decarbonize and produce less waste.

Technological innovation

Innovation will be critical to achieving the cement industry's sustainability potential, with promising avenues already emerging. For example, one start-up uses a lower proportion of limestone in its cement, which results in fewer process and fuel emissions; this company's process also locks in additional CO_2, which is added before the concrete cures. Adding CO_2 makes the concrete stronger and reduces the amount of cement needed. Carbon-cured concrete could also use CO_2 captured during cement production. Today's methods could sequester up to 5 percent of the CO_2 produced during production, but newer technologies could sequester 25 to 30 percent. Products such as carbon-cured concrete, positioned differently, could earn a "green premium," potentially giving companies an edge among environmentally conscious buyers—and greater pricing power.

On the horizon are CCUS technologies. While frequently costly and perhaps (for now) more suitable for making higher-value products such as steel rather than cement, by 2050, they could more than halve emissions. A number of postcombustion carbon-capture pilots are underway, driven by the large cement players. Other companies are testing oxyfuel combustion, a promising but expensive technology that results in high concentrations of CO_2 in flue gas, which in turn allows for near-total carbon capture.

Ultimately, capitalizing on technology and innovation will require more investment, as well as a shift in mindset for companies that have become too comfortable with the status quo. Many cement players are not used to relying on partnerships, or to operating in the kinds of ecosystems that are second nature in other industries. With innovation timelines of five to ten years, these companies could soon find themselves playing catch-up.

New growth horizons

Sustainability ultimately may be the catalyst that pushes the industry to seek growth via new business models, partnerships, and construction approaches. Cement-based concrete will remain the global construction material of choice, but "sustainable construction" value chains are likely to emerge on the regional and local levels, necessitating a reorientation of many corporate portfolios.

In the United Kingdom, for example, recycled material from construction and demolition waste is increasingly being used to replace aggregates in concrete. Cement makers have been slow to seize the opportunity, ceding the waste-recycling business to local construction companies. Meanwhile, in other markets, traditional cement may compete with an improved variety—energetically modified cement (EMC)—which releases less carbon and requires less energy to produce. EMC has already been used (in combination with traditional cement) for a variety of projects in Texas.

Other opportunities lie beyond cement and concrete. Alternative building materials and other approaches will likely play an important role in the

[2] *Technology roadmap: Low-carbon transition in the cement industry*, International Energy Agency, April 2018, webstore.iea.org.

decarbonization of the cement industry, though a great deal of uncertainty remains as to how much they will reduce emissions. For example, CLT is already used in a number of markets and has been buoyed by its reputation as a green material. Should roughly 10 percent of cement be replaced with CLT, carbon emissions would be reduced by up to 750 million tons each year (about 2 percent of global emissions).[3]

Additional new value pools include prefab and modular housing, which incorporate off-site production, and BIM. Greater transparency means less waste and likely a reduction in the amount of cement or concrete required. Indeed, digital technology is at once supporting the cement industry's decarbonization efforts and contributing to its growth challenges.

Getting started

Companies that hope to lead the industry's decarbonization efforts must identify the best path forward, pursue the right technological advancements, and rethink their products, portfolios, and partnerships. That said, making decisions on investments in the current asset footprint will remain a challenge. Possible solutions include building an abatement curve, establishing different scenarios, and creating a road map that allows decisions to be triggered based on the outcomes of different scenarios.

A twofold, systematic assessment of decarbonization options can provide transparency on existing levers and accelerate rollout while driving innovations in collaboration with other industries or sectors. This includes plant-specific assessments and creating heat maps and abatement curves as well as the evaluation of local ecosystem partnerships with start-ups, other value-chain players, or governmental institutions.

To understand the shifts in value pools, cement players should develop a vision of the future target portfolio and business model implications to capture the value of sustainable building solutions. The industry will remain a local business; hence, there remains the need to build this perspective micromarket by micromarket. From there, the findings should be elevated and cross-cutting opportunities, such as sustainable concrete, should be prioritized.

The success of such a strategy, however, depends on leaders' abilities to achieve an organization-wide mindset change that promotes rethinking the current way of working. Leaders should therefore consider the best ways for encouraging the entire organization in their decarbonization journey.

Cement makers are approaching a moment of truth. Challenges such as decarbonization, ongoing value-chain disruption, and competition against the construction ecosystem's entire patchwork of players all loom large. With the right mindset, decarbonization and reinvention can go hand in hand: just as automakers increasingly view their role as providing mobility, not just making cars, cement companies could likewise be in the business of providing construction solutions. As climate pressures increase and sales of traditional cement and concrete face threats, the combination of new thinking, innovation, and new business models will be critical to helping ensure a profitable—and greener—future.

[3] This would require the sustainable harvesting of about one-tenth of the existing boreal forest (located in the Northern Hemisphere). CLT comes with the advantage of considerable carbon sequestration: for each ton of carbon emissions avoided, two additional tons of carbon are sequestered.

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The authors wish to thank Eleftherios Charalambous, Rafal Malinowski, Lea Pollert, Eveline Speelman, Miriam Walden, and Hendrik Zuber for their contributions to this article.