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TOWARD A TRADABLE, LOW-CARBON CEMENT STANDARD

POLICY DESIGN CONSIDERATIONS FOR THE UNITED STATES

TARYN FRANSEN, KATIE LEBLING, DEBBIE WEYL, AND KEVIN KENNEDY

EXECUTIVE SUMMARY

Highlights

- A low-carbon cement standard that sets a limit on the emissions intensity of cement by using tradable credits can encourage the adoption of existing abatement opportunities while setting a clear regulatory road map to inspire long-term investment in deep emissions reductions.
- Cement producers and importers would generate or need to surrender credits based on their performance against an emissions intensity benchmark. These credits would be tradable, rewarding companies that reduce emissions intensity.
- Such a standard would provide a targeted incentive to catalyze decarbonization in the sector in a potentially more effective manner than under economy-wide carbon pricing. The standard would provide incentives to adopt existing abatement options and to invest in emerging technologies.
- Addressing the technological, financial, market, and other barriers to abatement in the cement-concrete value chain will require a suite of complementary policies. Although a low-carbon cement standard can play a significant role, additional policies will be needed to decarbonize the full cement-concrete value chain.
- This paper outlines design considerations for an effective low-carbon cement standard, including how to define an emissions intensity metric, set the benchmark stringency, establish a price ceiling and floor for credits, and address the risk of leakage and competitiveness concerns.

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Suggested Citation: Fransen, T., et al. 2021. "Toward a Tradable, Low-Carbon Cement Standard: Policy Design Considerations for the United States." Working Paper. Washington, DC: World Resources Institute. Available online at doi.org/10.46830/wriwp.20.00112.

The Cement Decarbonization Puzzle

Achieving the goals of the Paris Agreement will require decarbonizing the global economy, including heavy industry sectors such as cement. Cement production accounts for an estimated 1.2 percent of U.S. greenhouse gas (GHG) emissions and 7 percent of global carbon emissions (EPA 2020; IEA and CSI 2018). These emissions come from fuel combustion and the chemical reactions inherent in the production process. Around three-quarters of cement is used to make ready-mix concrete (USGS 2020).

Many opportunities to reduce the emissions intensity of cement exist or are in development. Options include reducing the clinker-to-cement ratio by using supplementary cementitious materials, fuel switching, carbon capture technology, energy efficiency, and the production of novel cements. Not all options would apply to all plants—some are not commercially available yet, are constrained by resource availablity, or are dependent on the use of certain inputs or plant-specific technologies.

A tradable, low-carbon cement standard would provide a targeted approach to reducing the emissions intensity of the cement sector. It would incentivize the wider adoption of existing abatement options today and establish a transparent regulatory road map to set the pace of decarbonization across the industry, incentivizing investment in more nascent technologies.

Although this paper focuses on a low-carbon cement standard, decarbonizing the sector would rely on complementary policies throughout the supply chain. Innovation policies can help advance early-stage technologies, financial and technical assistance can increase deployment for emerging technologies, and policies and programs that stimulate market demand can overcome resistance to change for market-ready technologies.

Design Considerations for a National Tradable Performance Standard for Cement

A low-carbon cement standard would create an emissions intensity benchmark for cement, with cement producers generating either credits or an obligation to surrender credits based on their emissions intensity relative to that benchmark. Because the credits are tradable, companies have a financial incentive to reduce their emissions intensity. As the benchmark is lowered over time, the standard can help drive innovation by increasing demand for abatement technologies.

Design considerations include defining an emissions intensity metric, setting and strengthening the benchmark stringency, and addressing competitiveness concerns and the risk of leakage. Preliminary recommendations include the following:

- Establish an emissions intensity standard that covers direct (Scope 1) and indirect (Scope 2) carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions per unit of clinker and mineral additives, using a default, grid-average emissions factor to calculate Scope 2 emissions.

- Set the standard at an initial stringency marginally lower than the current average emissions intensity to incentivize investment in currently available, cost-effective abatement options.

- Tighten the stringency of the standard annually, taking into consideration factors such as the need to achieve global net-zero CO_2 emissions before 2050 and net-zero GHG emissions by the 2060s to hold warming to 1.5°C, the expected contribution of the standard to reduce emissions (e.g., to meet an economy-wide emissions reduction target), available abatement options and their costs, and the magnitude of incentive required to accelerate innovation. The rate of decline should be updated every five years.

- Include a price floor and ceiling for credits, with the values for each taking into consideration the cost of abatement options and backstop carbon removal technologies.

- Apply the standard to imported cement in addition to domestic production, using a conservative default emissions factor for imported cement unless verified information is available.

Legal avenues for implementing a low-carbon cement standard at the federal level include passing new legislation or using the Clean Air Act. New legislation would provide an opportunity to more holistically design a low-carbon cement standard incorporating the best principles outlined in this paper. New legislation would likely incorporate multiple industries, rather than being cement specific, and so would likely require addressing integration across sectors. The U.S. Environmental Protection Agency could use its authority under the Clean Air Act to develop output-based emissions intensity standards for cement facilities to implement a low-carbon cement standard. Due to the scope of the Clean Air Act, this approach would limit emissions coverage to Scope 1, in contrast to the recommendation above. The Clean Air Act would not apply to importers of foreign cement, and maintaining the competitiveness of the U.S. industry could require policies to address competitiveness concerns of workers and the industry, potentially including a border tax adjustment, incentives for domestic low-carbon production, or other modifications to help provide a level playing field for domestic producers.

About This Working Paper

The primary objective of this working paper is to outline for policymakers and other stakeholders the key design considerations surrounding a low-carbon cement standard. It also provides an overview of the cement and concrete supply chain and industry dynamics, abatement options for cement production, and the suite of complementary policies that could be used in tandem with a low-carbon standard. Additional research is needed to quantify the prospective economic and environmental impacts of a low-carbon cement standard as well as other policy tools for decarbonizing cement and concrete. Such research would provide a basis for more detailed recommendations on designing a low-carbon cement standard.

A companion working paper considers the same issues for the steel industry.

1. THE DECARBONIZATION CHALLENGE FOR CEMENT AND CONCRETE

Achieving the goals of the Paris Agreement requires decarbonizing the global economy by midcentury. Cement production is responsible for just over 1 percent of U.S. greenhouse gas (GHG) emissions and about 7 percent of global emissions (EPA 2020; IEA and CSI 2018). Decarbonizing cement is especially challenging because the manufacturing process involves calcinating limestone to produce lime, which emits carbon dioxide (CO_2). It also requires high-temperature heat that is difficult to produce through electricity or renewable energy.

Along with concrete, cement is embedded in a complex ecosystem of long-standing construction practices that are unlikely to change without significant incentives (see Box 1). Other programs and policies that help create markets for low-carbon products, such as voluntary corporate and public green procurement, have provided incentives for the industry to begin reducing emissions, but the impact of these initiatives has been incremental. More transformative policy approaches are necessary to meet ambitious decarbonization goals.

1.1 The Role of a Low-Carbon Cement Standard

A low-carbon cement standard can serve dual purposes: it can move the market in the near term to meet initial emissions benchmarks through existing technological opportunities and set a clear regulatory agenda and road map to inspire long-term investment in deep emissions reductions. The standard will need to be one of a suite of policies, along with financial incentives and technical assistance to increase deployment, procurement policies that push deployment of market-ready technologies, and others.

One advantage of a sector-specific policy over a broader economy-wide approach like a cap-and-trade program or carbon tax is the ability to provide more targeted incentives to drive long-term change within the sector. Economic efficiency argues for an economy-wide approach that incentivizes implementing the lowest-cost abatement options first. However, prioritizing only currently low-cost options may fail to provide sufficient incentives for actions that reduce the cost of currently more expensive options, which are needed to improve the abatement options available over time (Gillingham and Stock 2018; Vogt-Schilb et al. 2018).

Box 1 | The Cement and Concrete Supply Chain

Concrete and cement are distinct products. Concrete is a mixture of a binding material with sand, gravel, and sometimes other materials that hardens with exposure to water into a stone-like material. It is used in the construction of buildings, roads, bridges, and other infrastructure. Cement is the most common binding ingredient in concrete.

Cement production is relatively centralized, with fewer than 100 cement plants in the United States. In recent years, these plants have produced about 87 percent of the cement used in the country, with the rest imported from Canada, Greece, China, and other countries.[a] Given the low value per ton of cement, it is costly to transport, and most cement plants serve a local or regional market. Because cement can be transported by sea more economically than over land, imports are largely limited to coastal regions.

The United States has more than 8,500 concrete plants, including both ready-mix and precast plants.[b] Around three-quarters of cement goes to ready-mix batch plants that mix hundreds or thousands of types of concrete specific to each project and pour it at project sites. Because ready-mix concrete must be used within hours of being mixed, the ready-mix plants are distributed throughout the country near demand centers to minimize transportation distances. A smaller portion of cement goes to precast concrete plants to make blocks or other concrete parts, cure them at the plant, and then transport them to end users.[c]

A wide variety of actors determine how concrete is mixed and used. These include the organizations that set standards to ensure material safety and performance; the developers and government agencies that purchase buildings, roads, and bridges; the architects and engineers who design them; and the contractors and construction workers who build them. Ready-mix plants produce various mixes based on the needs and desires of the end users. Although carbon emissions are of increasing interest to a portion of the market, the primary drivers for how concrete is used in construction have traditionally been the cost, safety, and durability of the final product.

Sources: a. USGS 2020; b. U.S. Census Bureau 2018; c. USGS 2020.

Sector-specific pricing programs can provide more targeted incentives to decarbonize sectors that might not respond to an economy-wide price. California's Low-Carbon Fuel Standard (LCFS) demonstrates this approach, and a similar approach can be used for manufactured products through a clean product standard (King et al. 2020). A low-carbon cement standard could place a high value on the incremental emissions reductions from cement production, giving a strong economic incentive to producers without applying that high price across the economy. Investments and subsidies, such as public investment in CO_2 transport or tax credits for carbon capture, use, and storage (CCUS), can also reduce the costs of abatement significantly and lead to more investment in the technologies necessary to realize deep decarbonization of cement and other industrial sectors.

1.2 The Scope of This Working Paper

This working paper explores the role that a low-carbon cement standard can play in shifting the cement and concrete industries. It highlights opportunities and barriers to technological abatement, how policy can help create opportunities and address barriers, and key policy design features for a tradable, low-carbon cement standard. It also notes areas needing further research and discussion.

Section 2 provides an overview of the cement and concrete industry. Section 3 then describes the policy context into which a low-carbon cement standard would fit before walking through key considerations for designing such a standard in Section 4. Next, Section 5 outlines legal avenues for implementing the standard. Appendixes A and B offer overviews of the key abatement options available for cement and concrete production, respectively. These provide important context for future consideration of the stringency of a low-carbon cement standard, though specific recommendations on the level of benchmarking stringency are beyond the scope of this paper due to data limitations.

Box 2 | What Is a Low-Carbon Product Standard?

As used in this paper, the term *low-carbon product standard* refers to a sector-specific regulation to provide incentives to reduce the carbon intensity of particular manufactured products.[a] This technology-neutral policy creates a tradable emissions intensity standard, or benchmark, for a set of defined products. Companies that make products covered by the standard generate credits if their emissions intensity is lower than the benchmark, or they generate obligations if their emissions intensity is higher than the benchmark. The amount of credits or obligations companies generate depends on the degree of emissions intensity above or below the benchmark. Because companies that generate credits can sell them to those that need to purchase them, the policy provides a financial incentive for companies to reduce the emissions intensity of their production process.

To the extent that the benchmark is lowered over time, the product standard can help drive innovation by increasing the need to reduce emissions intensity. In addition, clear signals about the expected trajectory of the benchmark—how much it will be lowered over what time frames—can provide long-term incentives for investment in innovation because companies know that innovation today can lead to longer-term financial benefits.

Section 4 describes the design of a low-carbon cement standard in more detail.

Sources: a. Fischer 2019; King et al. 2020.

The findings of this working paper are based on literature review and consultation with stakeholders involved in academia, policymaking, and industry. Industry data was retrieved from government sources; information on abatement options is from available literature and interviews with industry stakeholders and academic experts; and information on existing policies and policy design is from a combination of regulatory documents and academic literature. Data analysis is based only on publicly available data.

2. THE CEMENT AND CONCRETE SECTOR

U.S. cement plants are typically located near sources of their main raw input, limestone. They produce a handful of standard cement types (as well as a variety of specialized types) that are mostly sold to concrete producers. Concrete plants are more distributed and are located near demand centers to minimize the need to transport concrete. Concrete manufacturers produce hundreds to thousands of types of concrete, with unique mix designs depending on the buyer's specifications.

The supply chain from cement to concrete to final use involves a number of actors with varying incentives and preferences. Different technology and policy options, discussed below, can influence which products suppliers and purchasers choose to sell and buy.

The relative cost impact of decarbonizing the cement industry is very different at different points in the supply chain. Decarbonization at the cement plant adds significantly to the average cost of cement production, though this cost increase as a share of total cost is smaller for the concrete product made with this cement and is even smaller for the building or other structure made with the concrete. Fully decarbonizing the cement industry by mid-century could double the cost of cement once the transition is complete, with higher costs in the short term (ETC 2020). Cost increases for concrete would be less (around 30 percent) and much smaller on a final structure—for example, about a 3 percent increase on a $500,000 house because the cost of cement is a smaller portion of the total material or product cost toward the end of the supply chain (ETC 2020).

A low-carbon cement standard that applies to all cement sold in the United States—as opposed to just cement manufactured in the country—would help address concerns about foreign competition and make it easier to pass costs along the supply chain to end users, where the cost impacts are lower. The standard could be complemented by financial incentives and technical assistance that would help reduce the direct cost to industry in shifting to lower carbon production approaches. Policies would also be needed to ensure a level playing field with possible substitute products, such as steel, asphalt, and cross-laminated timber. Developing similar low-carbon standards for substitute products or enacting complementary policies that incentivize the purchase of low-carbon products could address this concern, although a full discussion of this issue is beyond the scope of this paper.

2.1 Cement Production and Emissions

In 2019, the United States produced 88.5 million metric tons (Mt) of cement at 96 plants across 34 states and Puerto Rico (USGS 2020). An additional 16 Mt of cement and clinker (the main ingredient in cement) were imported in 2019, and around 1 Mt were exported (USGS 2020). The United States is the third-largest producer of cement globally, following China, which produces more than half of the world's cement (2.2 billion metric tons in 2019) and India, which produced 320 Mt in 2019 (USGS 2020).

Ninety-two U.S. cement plants reported 67.2 Mt of CO_2 equivalent (CO_2e) in GHG emissions to the U.S. Environmental Protection Agency (EPA) in 2019 (EPA 2020), about 1.2 percent of total U.S. emissions that year (Houser and Pitt 2020). This number excludes emissions from electricity use in facilities but includes both emissions from fuel combustion and from calcination (often referred to as *process emissions*), or the chemical breakdown of limestone into lime, the main ingredient in cement. Recent data from the EPA do not differentiate between the two, but many other sources point to a ratio of roughly 60 percent of emissions coming from calcination and 40 percent from fuel combustion (ETC 2018; IEA and CSI 2018).

The cement production process involves quarrying limestone, grinding it, and combining it with other materials to achieve desired proportions of constituent oxides: calcium, silica, alumina, and iron (van Oss 2005). In most facilities, the mixture moves through preheater and precalciner units, where it is heated and calcination occurs. It then moves to the rotary kiln—a long, slowly rotating steel tube—where the mixture reaches around 1,450°C and undergoes sintering to form the minerals that allow cement to harden when exposed to water. The result is a golf ball–sized material called clinker.

Clinker is then cooled and typically ground with a small amount (around 5 percent) of gypsum and sometimes other materials. The resulting powder is cement. Cement produced in this manner is termed *portland cement* and is the most commonly used kind of cement worldwide. The five general types of portland cement differ in the proportions of mineral compounds and influence the characteristics important to materials specifications such as rate of strength gain. A number of other specialty cements and blended cements use portland cement with other supplementary cementitious materials (SCMs), such as steel slag (up to 70 percent), limestone (up to 15 percent), or pozzolans, including fly ash (up to 50 percent), and fall under a different materials standard.

Cement producers may be able to make incremental improvements in the near term—for example, energy efficiency improvements or fuel switching—to reduce emissions at existing facilities, but more significant investments will generally be needed to achieve transformational gains, such as with CCUS.

2.2 Concrete Production and Emissions

Globally, concrete is the most-consumed manufactured material—used in infrastructure from roads to bridges to buildings—and cement is the glue that holds concrete together. For the majority of its uses, cement is transported from cement plants to concrete batch plants. There, it can be mixed with SCMs such as fly ash, silica fume, or steel slag, which contribute to the desired properties of the end product, as directed by the architect or engineer. The cement mixture is combined with aggregate (sand and gravel of varying sizes) and water to form concrete. Concrete mixes are generally 55–80 percent coarse and fine aggregate, 15–20 percent water, 7–15 percent cement, and 0.5–8 percent air by volume (van Oss 2005). Around 70–75 percent of cement goes to ready-mix concrete plants, which mix specific types of concrete by project and pour it at project sites. A smaller portion goes to precast concrete plants, which make blocks or other concrete parts, cure them at the plant, and then transport them to end users (USGS 2020).

Although concrete is composed of up to 80 percent aggregate and usually only up to 15 percent cement, the carbon footprint of that cement contributes to nearly 80 percent of concrete's carbon footprint. The other 20 percent of emissions come from sourcing and preparing coarse and fine aggregate, water, and the mixing process (Gregory 2019).

The emissions intensity of cement is usually not a factor that concrete manufacturers consider when purchasing cement. Instead, they produce concrete mixes that meet the specifications of the final purchasers and meet industry standards, which cover essential, but not emissions-related, characteristics such as strength and time to strength gain.

2.3 Final Purchasers

The final purchasers of concrete, including public entities and developers, represent a diverse set of decision-makers. For many, the prioritization of safety and structural resilience leads to risk aversion, which can make broader change difficult, including the use of new low-emissions concrete mixes. The final users may be concerned that approaches that reduce the emissions intensity of concrete—particularly by altering ingredients or using less cement per unit of concrete—could risk insufficient strength or uncertainty around other attributes. Addressing the diverse needs of purchasers at the end of the supply chain requires addressing a range of requirements, including building codes and concrete specifications.

An important set of intermediate actors who influence and work with the final purchasers are the architects and engineers who determine materials specifications. Their decisions are critical: if they prioritize emissions in their designs and specifications, they can increase demand for low-emissions materials that meet the same performance characteristics. Creating this demand by shifting the preferences of final purchasers and those who influence them will require engagement programs to increase awareness and education about low-carbon design.

Concrete producers make products that meet the specifications of architects and engineers, and they sell those products to final users or purchasers, including public entities and developers. In recent years, some of these purchasers have begun to emphasize lower emissions as a characteristic of the concrete they purchase. Leading concrete producers can take advantage of near-term opportunities for lower-emissions concrete—either through the use of low-emissions cement, if product-specific emissions intensities are made available, or at the concrete production stage—to gain market share with first-moving customers who prioritize the emissions intensity of the final product. Environmental product declarations that provide the estimated emissions intensity of concrete are becoming common in the industry, though most currently use an industry average for emissions from cement manufacturing.

3. DECARBONIZING THE CEMENT AND CONCRETE INDUSTRY

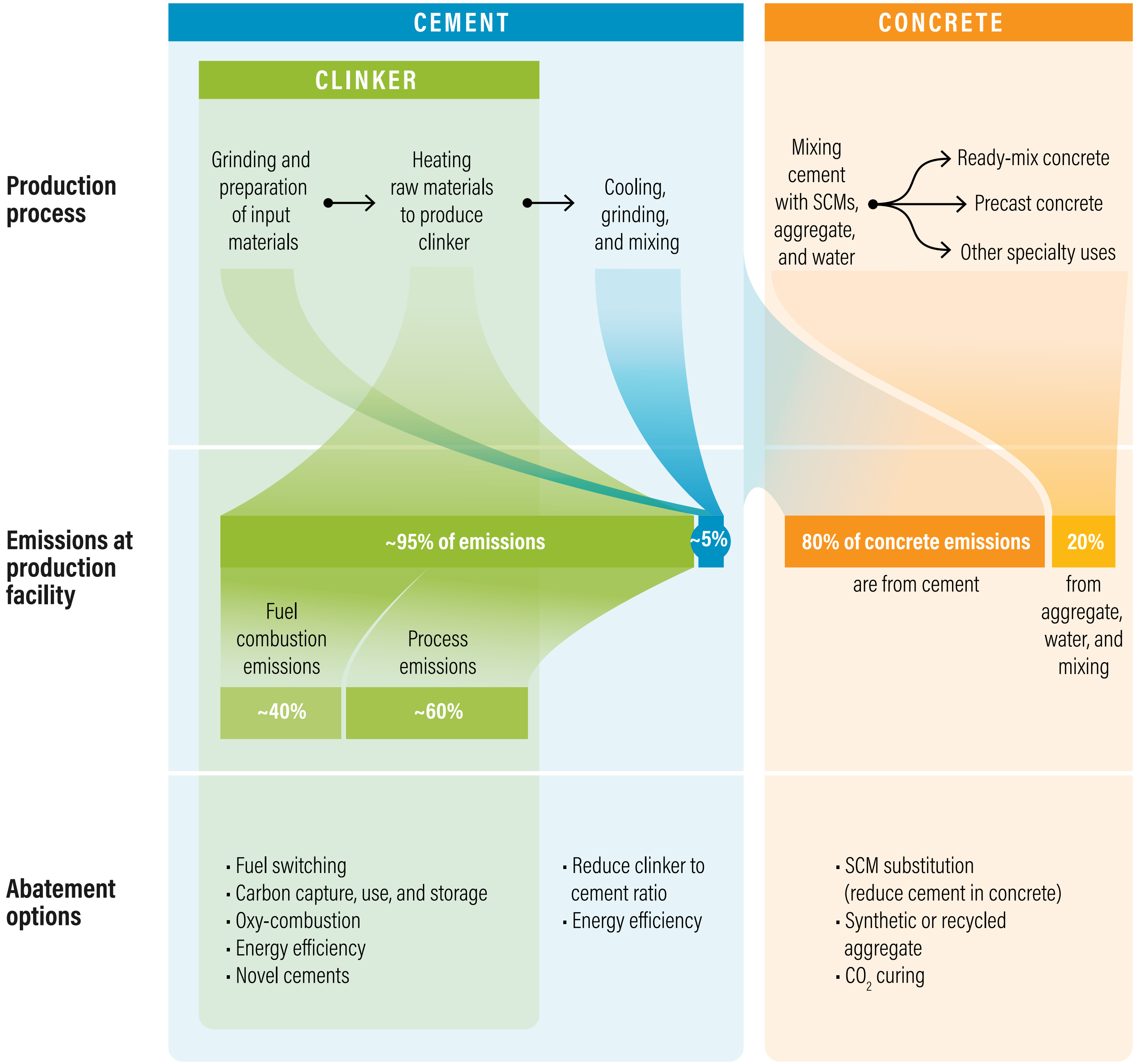
The Sustainable Development Scenario (SDS) of the International Energy Agency (IEA) suggests that, globally, emissions from cement production should fall from their current level of 2.4 billion metric tons of CO_2 ($GtCO_2$) in 2019 to around 0.8 $GtCO_2$ in 2050 to align with the goals of the Paris Agreement.[1] If the United States follows this trajectory, it would mean reducing emissions from 67.2 $MtCO_2$ in 2019 to 22.4 $MtCO_2$ in 2050. However, deeper reductions may be appropriate given a lower expected demand growth for cement in the United States compared to many other countries and a more mature economy. Both supply- and demand-side approaches can reduce emissions associated with cement by targeting the emissions intensity of production and the total demand for the product, respectively.

3.1 Abatement Options

A number of abatement options—both existing and in various stages of development—can be used to reduce emissions from cement production. This paper focuses on abatement options that could address emissions from cement manufacturing and would be within the scope of a national low-carbon cement standard (see Figure 1). Additional abatement is also possible through complementary policies that target the emissions intensity of concrete production as well as demand-side interventions that reduce demand for and increase recycling of concrete, avoid overbuilding and waste during construction, and promote longer-lived buildings and concrete recarbonation, among others.

The main options to reduce cement emissions include reducing the proportion of clinker in cement, fuel switching, using carbon capture technology or oxy-combustion, improving energy efficiency, and producing novel cements. Summaries of each abatement option are included in Table 1. A more detailed discussion of abatement options for cement (and concrete) can be found in Appendixes A and B.

Figure 1 | **An outline of the cement and concrete manufacture process, emissions, and abatement options**



Note: CO_2 = carbon dioxide; SCM = supplementary cementitious material. Demand-side interventions that could reduce demand for, and thus total emissions from, cement and concrete are not included in this graphic. Cement production steps that happen outside the cement plant (e.g., quarrying and transportation) are not included in this graphic because they would not be in the scope of a low-carbon cement standard.

Source: Adapted from Lehne and Preston 2018, with data from EPA 2020, Gregory 2019, and IEA and CSI 2018.

Table 1 | **A summary of abatement options and potential**

ABATEMENT OPTION	POTENTIAL
Clinker-to-cement ratio	The average ratio of clinker to cement in the United States is roughly 0.92 by weight.[a] This ratio can be lowered through increased use of blended cements, where supplementary cementitious materials (SCMs) such as fly ash can replace a portion of clinker at the cement plant. The extent to which this is possible depends on what material is used as a replacement, the needs of the final structure, and adherence to industry standards, which set allowable limits of SCMs in blended cements. Wider use of this option may be difficult in the United States, where SCMs are typically added at the concrete batch plant rather than the cement plant for economic and market structure reasons.[b] Some SCMs are also limited in total supply, may not be available in some regions, may be costly, and may not perform comparably to conventional materials (for example, they may result in slower strength gain in concrete).
Energy efficiency	Most of the more accessible energy improvements have been made already.[c] Meaningful gains could be made for the remaining worst-performing plants but would likely require investment in major new infrastructure such as kilns or grinding mills.
Fuel switching	Fuel combustion in the kiln produces around 27 million metric tons of CO_2 equivalent ($MtCO_2e$) per year (40 percent of the total 67.2 $MtCO_2e$ in 2019), which could be reduced by using a number of alternatives, including natural gas, waste biomass, and nonhazardous secondary materials.[d] More frontier options that are in development include hydrogen and electrification. The availability of alternative fuels is limited in total quantity, regional variability, and must be customized to each plant's current fuel mix (for which data are not publicly available). The use of alternative fuels such as nonhazardous secondary materials may require additional permits.
Novel cements	Novel cements use different ingredients than portland cement. Thus, these alternatives have the technical potential to replace a significant portion of portland cement, reducing or even eliminating process emissions. This will depend on which technologies and processes advance to wider use (and the net carbon footprint of their production process), the availability of their input materials, their cost, and whether there are limits on how these products perform relative to conventional cement and concrete.
Carbon capture, use, and storage (CCUS)	If implemented on all cement plants in the country, CCUS has the technical potential to capture up to 60 $MtCO_2$ in flue gas emissions (assuming a 90 percent capture rate as reported by Svante, a company that develops carbon capture technology for industrial processes).[e] The net capture amount may be lower depending on what energy source is used to power the capture system. CCUS has not yet been proved on a commercial-scale cement plant, though multiple projects are in progress. Its potential is currently limited by a lack of incentives to spur investment. CCUS may also not be viable on all plants, depending on the plant footprint and emissions control system as well as access to infrastructure to move captured CO_2, and availability of use or storage options for CO_2.
Oxy-combustion	Technical potential is up to 100 percent capture of flue gas emissions, or around 67 $MtCO_2$/yr.[f] Net carbon captured would be lower, considering the offsetting emissions from the materials and infrastructure needed for the process. Oxy-combustion technology is not yet demonstrated on cement plants.

Sources: a. PCA 2016; b. CSCME 2010; c. Gregory 2019; d. EPA 2020; IEA and CSI 2018; e. Svante 2020; f. EPA 2020; Ditaranto and Bakken 2019.

3.2 Policies to Decarbonize Cement

Decarbonization is currently limited by barriers such as cost, technological readiness, industry acceptance, and regional variability. For example, carbon capture technology has not yet been demonstrated on a full-scale cement plant, and both capture and transport infrastructure remain costly to deploy. Fuel switching may be difficult due to regional variability and permitting needs. In addition, abatement options based on modifications to plant equipment and operations, such as carbon capture and fuel switching, will require those facilities to update their air quality and other environmental permits, posing an administrative barrier. Other options, such as electric and hydrogen- or oxy-fired kilns, have not reached technological maturity.

The adoption of some abatement options is also constrained by industry specifications that generally focus on input materials rather than performance. New types of cement, which could perform comparably to conventional cements, may see slow uptake because they use different input materials than those in current industry specifications.

Addressing the barriers to abatement will require a suite of policies. Although this working paper is focused on the design of a low-carbon cement standard, decarbonizing the full cement-concrete value chain will require complementary policies, as outlined below and in Table 2.

Innovation policies foster technology development. For new technologies and processes, innovation policies facilitate research, development, and demonstration (RD&D), building out the solution set and bringing down costs for existing technologies. These might include policies such as direct investment in RD&D, financial support for front-end engineering design studies, and loan guarantees to support demonstration projects (such as those available through the U.S. Department of Energy's Title 17 program).

Financial and technical assistance policies support early-stage adoption and deployment. Financial and technical assistance policies can support the adoption and deployment of more mature decarbonization technologies. These policies might include technical assistance for emissions reductions (such as through the EPA's Energy Star Focus on Energy Efficiency in Cement and Concrete Production and the Department of Energy's Better Buildings, Better Plants program), subsidized loans, tax credits for low-carbon processes or products, and tax-advantaged financing structures. These policies can also help increase awareness of the available and emerging technologies.

Market-demand policies support scaled-up deployment. Once technologies and products are market ready, they often need deployment support from policies that stimulate market demand. Without these types of policies, low-emissions products may still face cost premiums or markets resistant to change, both of which slow widespread uptake.

- **Product-focused policies and programs** can stimulate early demand to enable broader deployment. These include voluntary corporate procurement programs, government procurement incentives or requirements, **low-carbon product standards** (the focus of this paper), and performance-based building codes or voluntary building certifications that include low-carbon materials.
- **Facility-based emissions control policies and programs** stimulate market demand with policies focused at the facility level, including facility-based GHG emissions standards, cap-and-trade programs, or a carbon tax.

Table 2 | **Example policy options to address barriers to scale up cement abatement options**

POLICY TYPE	EXAMPLE POLICY OPTION	POLICY OBJECTIVE
Innovation policies	Increased investment in research, development, and demonstration	Improve technological readiness of CCUS, development of oxy-combustion and hydrogen fuel switching, and development and demonstration of novel cements
Financial and technical assistance policies	Section 45Q of the U.S. tax code, which could be extended and expanded	Reduce cost of carbon capture
	Other federal tax credits, including reauthorizing the 48C advanced manufacturing tax credit and expanding its scope	Increase deployment of industrial decarbonization technologies, processes, and/or products
	Technical assistance for emissions reductions	Increase deployment of commercially available energy efficiency technologies, including capital investment strategies
Product-focused market demand policies	Government and institutional product-focused procurement incentives and requirements	Demonstrate effectiveness of and build initial demand for low-carbon cement and concrete
	Low-carbon product standards	**Transform the whole market for low-emissions cement or concrete, with decreasing emissions thresholds over time**
	Performance-based building codes	Create market demand for low-emissions concrete used for buildings
Facility-focused market demand policies	Cap-and-trade program or carbon tax	Improve cost competitiveness of low-carbon options by pricing carbon emissions
	Government and institutional entity-focused contract requirements	Require specific future abatement actions in return for access to large customers

Note: A low-carbon product standard for cement is the subject of this paper.
Source: WRI authors.

4. DESIGNING A LOW-CARBON CEMENT STANDARD

A low-carbon cement standard is a tradable performance standard for cement. The standard is based on a performance benchmark for emissions intensity per unit of product that gains stringency over time. Companies that make cement with an emissions intensity below the benchmark generate credits, whereas companies that produce cement with an emissions intensity above the benchmark must surrender credits accordingly. Because the credits are tradable, those with credits can sell them to companies that need to surrender them (Fischer 2019). Unlike a cap-and-trade program, where regulated entities must surrender allowances for their total emissions, only emissions above a benchmark create an obligation under a tradable performance standard. An example of a tradable performance standard is California's LCFS, which operates in parallel to California's cap-and-trade program.

A low-carbon cement standard can serve as part of a climate change policy portfolio. It can help drive the process of decarbonizing the cement sector by providing a targeted incentive to reduce emissions intensity. Moreover, because firms would pay only for emissions in excess of the benchmark (and not for their total emissions), only the least-efficient production incurs a cost. Finally, because permits are tradable and provide revenue, firms have an incentive to continue reducing emissions intensity even if they are already below the benchmark.

In the following sections, we discuss the design considerations for a low-carbon cement standard, including the product to be covered, crediting and point of regulation, how to set the benchmark and at what level, and how to address the threat of leakage. We have approached these design questions from the perspective of implementing the standard through stand-alone legislation, which offers the greatest flexibility in design. Alternate mechanisms may be possible under existing legal authority, though such approaches would affect the design options available.

4.1 A Cement Standard or a Concrete Standard?

The first important choice in the design of the standard is whether to apply it to cement or concrete. Although we have chosen to focus this paper on a cement standard, we carefully considered both options. In making this choice, we sought to balance considerations of the number and size of facilities in each segment of the industry, the emissions profiles of cement and concrete producers, the abatement opportunities available to each, and other considerations.

Fewer than 100 cement plants operate in the United States. The basic emissions reporting infrastructure is in place since most of them report their GHG emissions as well as their cement and clinker production to the EPA (EPA 2018). However, this reporting only applies to U.S. production and not to the approximately 15 percent of cement that is imported.

Concrete manufacturers are much more numerous, with over 8,500 in the United States, about half of which have 10 or fewer employees (U.S. Census Bureau 2018). Concrete also has a very high product diversity, with many batch plants creating a wide variety of mixes based on customer requirements and the end use of the product. For example, the concrete used in pavers will be different from what is needed for a dam, a nuclear power plant, or a bridge. Concrete mix designs can include varying proportions of water and air, varying sizes and weights of aggregate, different types and amounts of SCMs, and different proportions of cement to influence characteristics such as the workability of the mixture and the strength and durability of the end product. Though it also comes in different types, cement is a much more uniform product.

Because the primary emissions related to concrete are in the cement manufacturing process, emissions from concrete should be considered on a life cycle basis. Environmental product declarations (EPDs) that report life cycle emissions from concrete production are becoming more standardized and more common in the industry. These declarations are developed by product manufacturers and include information about the environmental impact of a product from its input materials and production process. An EPD is a disclosure tool meant to assess the relative environmental impacts across products and inform decision-making by buyers or other interested parties. In the context of cement and concrete, EPDs provide information about the carbon emissions associated with producing the product, among other information, though EPDs for concrete often use an industry average for emissions from cement production. EPDs do not currently offer the same rigor as the mandatory emissions reporting to which cement facilities are subject.

As discussed earlier, around 80 percent of emissions from concrete come from the production of cement. Near-term opportunities exist to reduce the emissions from cement plants through improved energy efficiency, fuel switching, and reducing the amount of clinker in the cement produced. Deep emissions reductions, however, will require either major investments in carbon capture or oxy-combustion or the large-scale deployment of novel cements. Concrete producers also have significant opportunities to reduce the embedded carbon emissions in their product by using less cement, increasing the use of SCMs, and using synthetic or recycled aggregate.

These considerations point in opposite directions. In terms of administrative ease and directly targeting the main emissions source, a cement standard is the best option; yet this approach misses significant near-term abatement opportunities at the concrete plants and complicates the treatment of imports. Nonetheless, for a national standard, we find that the relative administrative ease of applying the standard to the smaller universe of cement plants, which already report their emissions to the EPA, outweighs the advantages of applying the standard to concrete.

4.2 Crediting and Point of Regulation

U.S. cement producers and importers would be subject to the performance standard (see Section 4.6). Producers and importers would have a compliance obligation to surrender credits equal to the quantity of emissions produced in excess of the amount allowed by the standard. Conversely, producers and importers would generate credits if their emissions were lower than the level allowed by the standard.

Cement producers would either generate or be required to surrender credits as follows:

$$credits = performance\ standard_{\frac{tons\ CO_2e}{tons\ product}} * production_{tons\ product} - emissions_{tons\ CO_2e}$$

When *credits* is a positive value, credits are generated; when it is negative, credits must be surrendered.

Performance standard refers to the emissions intensity benchmark below which credits are generated and above which credits must be surrendered and is expressed in units of CO_2e per units of product. *Production* is the volume of product (e.g., cement) produced by a facility and is expressed in units of product. *Emissions* is the volume of GHG emissions produced by the same facility and is expressed in units of CO_2e.

Cement importers would either generate or be required to surrender credits in a similar manner:

$$\begin{aligned} credits = {} & performance\ standard_{\frac{tons\ CO_2e}{tons\ product}} * imports_{tons\ product} \\ & - emissions\ factor_{\frac{tons\ CO_2e}{tons\ product}} * imports_{tons\ product} \end{aligned}$$

Because regulators would be unable to require emissions and production reporting by foreign manufacturers, as they would for domestic manufacturers, cement imports could be assigned a default emissions factor. Such a default factor should be set conservatively by the regulator to ensure that imports do not gain an unfair advantage. Regulators could also provide the option to override the default emissions factor in cases where the importer can provide a verified custom emissions factor.

4.3 Defining an Emissions Intensity Metric

Because the standard is based on an emissions intensity metric, policymakers must first choose the numerator (emissions to include) and denominator (product definition).

Most previous experience with benchmarking cement's emissions intensity stems from the allowance allocation under cap-and-trade programs, where the quantity of allowances allocated is based on production quantity multiplied by an emissions intensity benchmark. For a low-carbon cement standard, the benchmark would be used to determine the quantity of tradable permits that a producer would either generate (by producing at an emissions intensity below the benchmark) or be required to surrender (by producing at an emissions intensity above the benchmark). These differences in objectives may suggest different approaches to setting the stringency of the benchmark, but cap-and-trade programs nevertheless offer insights on constructing the benchmark.

The discussion below offers approaches and considerations for defining first the numerator (GHG emissions) and then the denominator (cement product).

4.3.1 Defining the Numerator: GHG Emissions

Defining the numerator entails two decisions: deciding whether the emissions scope should include only direct emissions or also some indirect emissions and deciding which gases to include.

Direct emissions, also known as Scope 1 emissions, are emissions from sources owned or controlled by the reporting company—in this case, the regulated facility (WRI and WBCSD 2004). Only Scope 1 emissions are included in the mandatory GHG reporting program. Indirect emissions are a consequence of the operations of the reporting company, but they occur at sources owned or controlled by another company. They include Scope 2 emissions, which are associated with the generation of electricity, heating, cooling, or steam purchased by the reporting company for its own consumption; and Scope 3, which are all other indirect emissions not included in Scope 2. In the case of cement, direct emissions stem from calcination from clinker production and fuel combustion in the kiln. Direct emissions from the U.S. cement sector in 2019 were 67.2 $MtCO_2e$. The sector also consumes around 10 billion kilowatt-hours of purchased electricity per year (EIA 2020a), generating an additional 4 $MtCO_2e$ in Scope 2 indirect emissions.[2] (This paper does not consider Scope 3 emissions, which are difficult to account for and over which cement facilities have limited control.)

Table 3 summarizes the possible effects of three options for treating Scope 2 emissions. Limiting the standard to Scope 1 emissions would fail to incentivize investing in electricity efficiency and in choosing zero-carbon electricity where it is available. It also introduces the possibility that manufacturers might shift some energy needs from regulated Scope 1 sources to purchased electricity, without necessarily reducing net emissions. However, including Scope 2 emissions could introduce geographic inconsistencies; the standard may be more burdensome in certain areas due to regional variations in cost and the availability of low- and zero-carbon electricity.

Table 3 | The effects of including or excluding Scope 2 emissions

	EXCLUDE	INCLUDE	INCLUDE AT DEFAULT EMISSIONS FACTOR
Incentivize electricity efficiency	✗	✓	✓
Incentivize choosing zero-carbon electricity	✗	✓	✗
Avoid introducing geographic inconsistency	✓	✗	✓
Avoid incentivizing shifting energy use from Scope 1 to Scope 2	✗	✓	✓

Source: WRI authors.

In light of these considerations, **we recommend that the standard include Scope 2 emissions, but that it assign them a default, grid-average emissions factor.** This approach, which is used by the EPA's Energy Star program, would incentivize efficiency investments, avoid geographic inconsistency and activity shifting from Scope 1 to Scope 2, and require only a simple accounting approach. If regulators deem it important to incentivize cement manufacturers to work with utilities on providing zero-carbon electricity, they could supplement our recommended approach with a provision that would allow facilities to override the default emissions factor if they can demonstrate that they have entered into an appropriate agreement with a utility or other electricity provider. We do not consider this the primary purpose of a low-carbon cement standard, however.

In addition to specifying the scope, the numerator also needs to specify which GHGs should be included. In the case of cement production, the vast majority of direct emissions are from CO_2. However, small amounts of methane (CH_4) and nitrous oxide (N_2O) emissions are possible from stationary combustion in the kiln, and the EPA requires facilities to report on these emissions (EPA 2018). **We recommend that the numerator include CO_2, CH_4, and N_2O emissions from industrial processes and fuel use expressed in units of CO_2e.**

4.3.2 Defining the Denominator: Cement Product

Regulators must also define a denominator for the standard, in terms of units of product. These are the three options for defining the product:

- Clinker
- Cement (clinker plus mineral additives, such as gypsum and limestone)
- Cementitious materials (clinker plus mineral additives plus SCMs) (CARB 2010)

Cement can be made less emissions intensive by increasing the ratio of mineral additives and/or SCMs relative to clinker. Stakeholder consultations on California's cap-and-trade program suggested that manufacturers have some latitude to substitute mineral additives for clinker, but they have limited flexibility regarding SCMs because these are set by customer specifications (CARB 2010). SCM availability also varies significantly by geography. In the United States, it is customary to add SCMs at the concrete manufacturing stage, whereas in other parts of the world, this is done at the cement stage. Including SCMs in the product definition, therefore, would complicate comparisons of U.S.- and foreign-manufactured cement. **We recommend that the denominator include clinker and mineral additives.**

It is worth noting that depending on how the product is defined, it may exclude certain forms of novel cements (if they are not made out of the materials included in the product definition). This is unlikely to limit the effectiveness of the standard in the near term, but regulators should consider a provision to revisit this issue if and when novel cements become more common.

4.4 Benchmarking and Stringency

Once the emissions intensity metric is defined, policymakers should gather data from industry to determine the distribution of emissions intensity across the regulated entities. The program stringency will typically be defined with reference to these values—for example, as a percentage below mean emissions intensity. California set its benchmark for cement at the intensity of the best performer. (For other industrial facilities, California sets the benchmark at 90 percent of the average emissions intensity of in-state producers, but in the case of cement, no producer had an intensity as low as 90 percent of the average.) The European Union set its benchmark to equal the average of the 10 percent of producers with the lowest emissions intensity. Setting the stringency is a critical decision since it will determine the emissions abatement that the program generates and will also be a critical factor in program cost. **We recommend setting the benchmark at an initial stringency that is marginally below the current average emissions intensity in order to incentivize investment in available, cost-effective abatement options in the near term.**

A critical consideration is how to strengthen the standard over time. Certain abatement opportunities, such as some types of energy efficiency improvements and fuel switching, are available today at low cost. Opportunities such as CCUS and novel cements will take longer to reach technological maturity, but they may ultimately deliver greater total abatement potential as their costs fall over time. Therefore, the standard should be designed to increase stringency over time. A key consideration regarding the pace of this increase is the rate at which CCUS, novel cements, and other transformative technologies can be deployed in the cement sector, recognizing that both the capital-intensive nature of the industry limits the speed with which new technologies roll out and that a low-carbon cement standard itself could affect the market for transformative technologies; thus, these considerations are interrelated. **We recommend strengthening the stringency through an annual decline in the benchmark. The rate of decline should take into consideration factors such as the need to achieve global net-zero CO_2 emissions before 2050 and net-zero GHG emissions by the 2060s to hold warming to 1.5°C, the expected contribution of the low-carbon emissions standard to reduce emissions (e.g., to meet an economy-wide emissions reduction target by 2030), the available abatement options and their costs, and the magnitude of incentive required to accelerate innovation. The rate of decline of the benchmark should be updated every five years to reflect changes in the industry and other conditions.**

4.5 Cost Containment

Regulators will need to analyze current emissions intensity and abatement options to establish the declining emissions intensity benchmark, and this analysis will provide a basis for estimating the future supply of and demand for credits. However, a mismatch in supply and demand could result in very high or very low prices for credits. Establishing cost-containment measures such price ceilings and floors can generate economic benefits by limiting such spikes and lulls, as summarized in Wang et al. (2021).

Price ceilings and floors set a maximum and minimum price, respectively, on the cost of a credit (or ton of carbon). A price ceiling such as the one in place in California's LCFS can ease the concerns of industry by providing certainty via an upper cost limit. However, a price ceiling fails to incentivize abatement that costs more than the ceiling, which could reduce economic efficiency. A price ceiling could be set at the expected cost of backstop abatement technology such as direct air capture. Recent studies have suggested that the cost of direct air capture could fall to $150–$200 over the next decade (Baker et al. 2020; Keith et al. 2018). A price ceiling at that level would avoid forcing cement producers to invest in abatement that is more expensive than this backstop technology.

A price floor would further enhance price predictability, offering greater certainty in decisions to invest in emissions reductions. For example, a price floor can avoid very low allowance prices like those seen in the early phases of the EU emissions trading scheme. Providing an upper limit on credit prices might give regulators greater confidence in setting an ambitious trajectory for the declining benchmark, and a price floor would send a clear signal of commitment to decarbonization, even if regulators set too low a benchmark.

Another possibility is to broaden the suite of abatement options capable of generating credits for compliance under the program. This could be done by allowing credit trading with other programs (e.g., a tradable performance standard for steel) or by allowing the generation of credits for activities outside the cement facility, such as direct air capture or the production of synthetic aggregates from captured CO_2.

We recommend establishing a price ceiling and floor. The specific levels of each should be determined in parallel with determining the stringency of the program and should take into consideration the current and expected future costs of key abatement technologies and backstop carbon removal technologies.

4.6 Leakage and Competitiveness

Leakage occurs when mitigation policy in one jurisdiction results in increased emissions outside of that jurisdiction (IPCC 2014; Fischer 2015; Görlach and Zelljadt 2018; King et al. 2020). Leakage can occur through various channels. If the policy imposes greater costs on industry within its jurisdiction, the industry can lose market share to foreign competitors (competitiveness or trade channel), causing emissions to increase in unregulated jurisdictions even as they decrease in the regulated jurisdiction. In addition to compromising environmental effectiveness, the same channels that create emissions leakage can also reduce the economic efficiency of emissions reductions and compromise industry competitiveness in the jurisdiction with the mitigation policy (Görlach and Zelljadt 2018). A sector's vulnerability to leakage is sensitive to the emissions intensity of both domestic and foreign industry as well as how responsive foreign production is to changes in domestic production (Fowlie and Reguant forthcoming).

Given the difficulty of estimating these factors, domestic emissions intensity and trade exposure are often used as proxies in policy settings. Cement is widely considered to be both emissions intensive and trade exposed. In 2019, the United States produced approximately 88.5 Mt of portland and masonry cement and 78.0 Mt of clinker. It imported 15.0 Mt of hydraulic cement and 1.1 Mt of clinker for consumption, and it exported 1.0 Mt of hydraulic cement and clinker. The largest sources of cement imports to the United States are Canada, Greece, China, and Turkey (Table 4). The carbon intensity of U.S. cement imports relative to domestically produced cement is unclear. If U.S. cement is substantially more emissions intensive than imports, as suggested in some gray literature, then emissions leakage from regulating U.S. industry becomes a relatively smaller concern. (Emissions from transporting imported cement also factor into this equation.) The United States could, however, still lose market share. Moreover, the viability of substituting imported cement for domestically produced cement is not geographically uniform—it is much more plausible in coastal markets with access to ports.

Table 4 | **U.S. cement import shares by country of origin**

COUNTRY OF ORIGIN	IMPORT SHARE (%, 2015–18)
Canada	35
Greece	16
China	14
Turkey	11
Other	24

Source: USGS 2020.

Cap-and-trade systems, including those in California and the European Union, have attempted to mitigate leakage by subsidizing allowances for emissions-intensive, trade-exposed sectors. This option would not be viable in a performance-trading system specifically targeting the cement sector. A low-carbon cement standard would be somewhat less susceptible to leakage than a cap-and-trade system because only the share of emissions that exceeds the benchmark would be subject to an emissions price. Nevertheless, some leakage is possible.

To address the potential for leakage, **we recommend applying the performance standard to importers of foreign cement in addition to domestic producers.**[3] In the first case, imported cement could be assigned a default emissions intensity value by country of origin, which importers could opt to override based on verified data. Importers would be required to surrender credits for imported cement with an intensity in excess of the performance standard, just as would domestic producers, or pay an equivalent tariff. Domestic producers could likewise be eligible for additional subsidies to improve their performance, mitigating the competitive impact of the standard.

5. LEGAL AVENUES FOR A LOW-CARBON CEMENT STANDARD

The legal avenues for implementing a low-carbon cement standard at the federal level include passing new legislation and using the Clean Air Act.

New legislation is the preferred route because it would provide an opportunity to comprehensively design a low-carbon cement standard incorporating the best principles outlined in the sections above. If new legislation were passed, it would likely be broad based rather than cement specific, so it would need to address questions of integration across sectors. In addition, if the political will exists to pass new legislation that includes a low-carbon cement standard, there would likely be other related procurement or RD&D policies that would need to be considered in the program timeline, benchmarks, and design. Incremental steps toward creating a low-carbon cement standard, such as implementing a federal "buy clean" procurement policy, might be possible without new legislation.

The Clean Air Act (Sections 111[b] and 111[d]) gives the EPA jurisdiction to regulate air pollution from new and existing cement facilities, respectively. There are pending legal questions about its use for regulating GHG emissions, the ability to use tradable standards, and federal versus state jurisdiction in setting emissions thresholds. However, there is also a reasonable expectation that the EPA's authority would withstand judicial review.[4]

Application of these provisions to implement a clean product standard would require developing output-based emissions intensity standards for cement facilities, which is an approach the EPA has previously taken for other sources, such as electricity generating units. Because Section 111 regulates facility emissions, this approach would mean limiting the emissions covered to direct emissions and not including those associated with purchased electricity. The Clean Air Act would not apply to importers of foreign cement, and maintaining the competitiveness of the U.S. industry could therefore require policies to address the competitiveness concerns of workers and industry, potentially including a border tax adjustment, incentives for domestic low-carbon production, or other modifications to help ensure a level playing field for domestic producers.

6. CONCLUSIONS AND RECOMMENDATIONS

A low-carbon cement standard can address economic, market, and awareness barriers by transforming the whole market, with decreasing emissions thresholds over time. Such a policy would move the market in the near term to meet initial requirements through market-ready technologies while setting a clear regulatory agenda and road map to inspire long-term investment in deep emissions reductions.

Fully addressing the technological, financial, and other barriers to abating emissions in the cement-concrete value chain will require a suite of complementary policies. Although this working paper is focused on the design of a low-carbon cement standard, this single policy in isolation will be insufficient to decarbonize the full cement-concrete value chain. Additional policies focused on innovation will be necessary to advance early-stage technologies, financial and technical assistance will be critical to increase deployment for emerging technologies, and policies and programs that stimulate market demand (including, but not limited to, a low-carbon cement standard) will help overcome resistance to change for market-ready technologies.

This paper outlines considerations for policymakers to design an effective low-carbon cement standard that takes into account how to define an emissions intensity metric, how to set the benchmark stringency and at what level, and how to address competitiveness concerns and the risk of leakage.

- Designers of a low-carbon cement standard should establish a benchmark that covers direct (Scope 1) and indirect (Scope 2) CO_2, CH_4, and N_2O emissions per unit of clinker and mineral additives, using a default, grid-average emissions factor to calculate Scope 2 emissions.
- This standard should start at a level marginally below the current average emissions intensity to incentivize low-cost interventions in the near term. It should tighten on an annual basis to progressively incentivize investment in more nascent solutions, with the rate of decline updated every five years. Considerations in setting and tightening the stringency include the need to achieve global net-zero CO_2 emissions before 2050 and net-zero GHG emissions by the 2060s to hold warming to 1.5°C, the expected contribution of the low-carbon emissions standard to reduce emissions

(e.g., to meet an economy-wide emissions reduction target by 2030), available abatement options and their costs, and the magnitude of incentive required to accelerate innovation.

- The standard should include a price ceiling and floor for credits. These values should be developed in parallel with the program's stringency, and they should consider the expected costs of abatement for the cement industry and of backstop carbon removal technologies.
- The standard should apply to importers of foreign cement in addition to domestic producers, using a conservative, default emissions factor for imports unless the importer can provide verified alternative emissions details.

APPENDIX A: ABATEMENT OPTIONS IN CEMENT PRODUCTION

Abatement options that could apply to cement production are described below. These include approaches that are already in practice as well as those in development and not yet commercially available.

A.1 Clinker-to-Cement Ratio

SCMs can be blended into cement at the cement plant to reduce the proportion of clinker and thus the carbon intensity of cement. The extent of substitution depends on the material used and the cement type needed. Along with use of novel cements, which are not widely available yet, this approach changes the ingredients in cement rather than the cement production process, so it may face barriers related to consumer demand. At the same time, it could be a relatively less expensive option given that new equipment is generally not needed.

The average clinker-to-cement ratio in the United States is 0.92 compared to 0.72 in Europe and even lower elsewhere (Lehne and Preston 2018; PCA 2016). However, the differences in these ratios are largely a result of SCMs generally being added at concrete plants in the United States for historical and market structure reasons (CSCME 2010), whereas they are more likely to be added at cement plants in Europe. Thus, although the clinker ratios in cement differ, the portion of clinker in concrete is roughly equivalent in the end, with the difference lying in where in the process the SCMs are added.

Possible SCMs include natural pozzolans, fly ash, and steel slag, among others. Portland limestone cement, which includes up to 15 percent interground limestone, has gained traction Europe, where it makes up around a third of cement sold (Favier et al. 2018), and is seeing increasing interest in the United States. It was added to the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO)[5] standards in the United States in 2012 and is approved by most state departments of transportation (with a few notable exceptions, such as California).

A.2 Energy Efficiency

The biggest portion of energy use at a cement plant comes from the components and processes used to heat the raw materials. The most efficient systems today use a dry process with preheaters and precalciners, which use recovered excess heat, before raw material enters the kiln (ETC 2018). Wet process kilns, which are less efficient due to the energy needs for water evaporation, are in the minority and are being retired. Data from 2017 indicates that 84 plants in the United States used a dry kiln (accounting for 97 percent of production), 7 used a wet kiln, and 1 used both (Curry and van Oss 2020).

Aside from infrastructure replacement, other efficiency gains could be realized in improvements to raw materials preparation, the clinker production process, or finish grinding, impacting either fuel use in the kiln or electricity usage at the plant (Worrell et al. 2013).

Analysis from 2011 shows that cement manufacturers in the United States improved their energy efficiency by 13 percent over the preceding decade, with the worst-performing plants seeing the largest improvement (Boyd and Zhang 2011). Remaining opportunities will likely require significant investment (Gregory 2019).

A.3 Fuel Switching

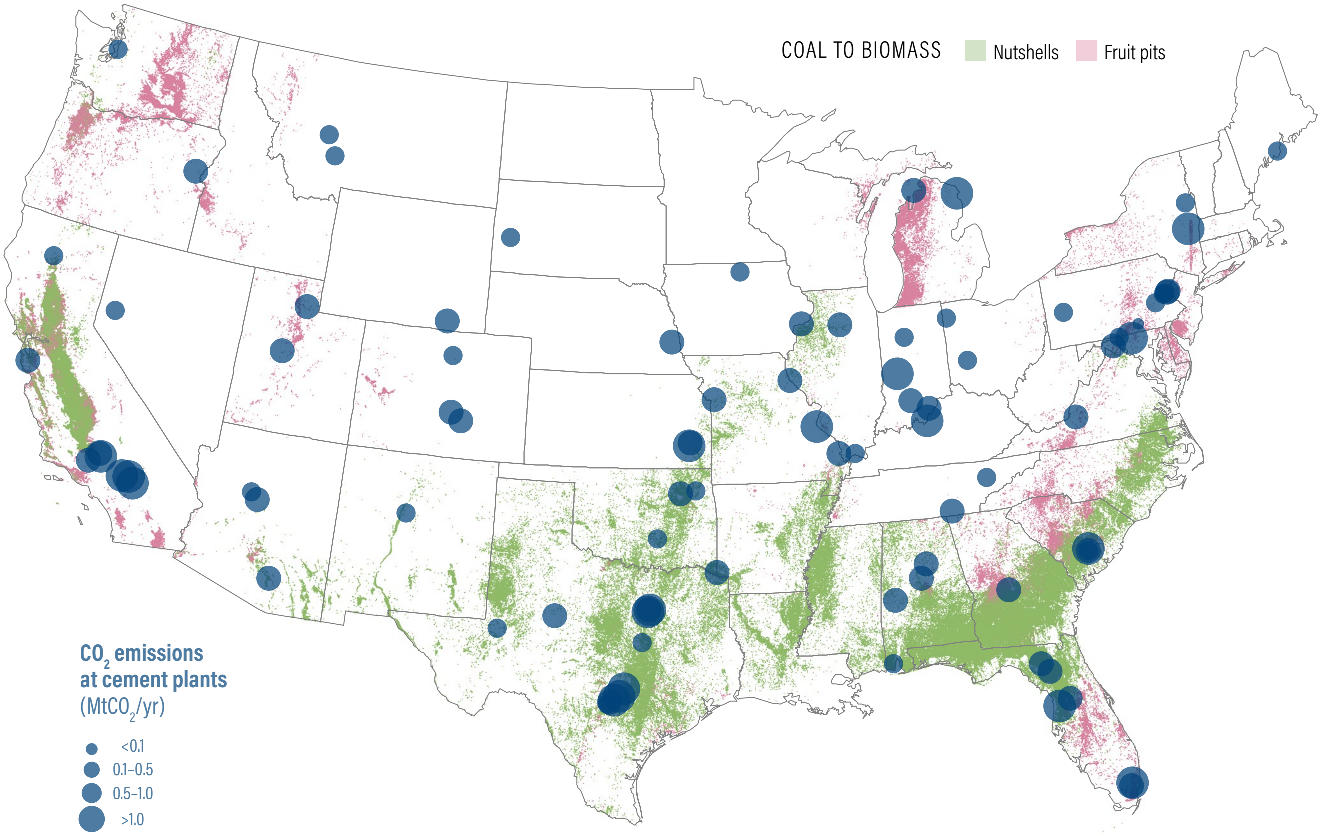
Fuel switching can reduce emissions by using fuels that are less emissions intensive. Because of the high temperatures required for cement production, U.S. cement kilns predominantly use fossil fuels along with some waste material and biomass. The fuel composition in U.S. cement kilns is dominated by coal and coke (64 percent), natural gas (20 percent), and tire-derived fuels (5.5 percent) (EPA 2019). In 2018, bioenergy and biomass-based wastes provided less than 1.6 percent of fuel used for cement production in the United States (PCA 2020).

Fuel switching can include a range of options, including natural gas in place of some coal and coke, carbon-dense waste biomass in place of coal, and biogas in place of natural gas as well as nonhazardous secondary materials like tires, engineered municipal solid waste, or even hazardous materials. Despite the potential, various challenges limit the current use of these alternatives. For example, although natural gas would reduce emissions compared to coal and coke, it may require pipeline expansion; substituting biomass waste (e.g., nutshells and fruit pits for coal; Figure A1) has a finite total supply available with regional variability and may face potential competition for other uses.

Nonhazardous secondary materials have the potential for greater use, but they may face barriers related to permitting requirements. Policy changes could help incentivize greater use of other types of waste that would otherwise go to landfills or be incinerated. For example, recent data indicate that alternative fuels make up 36 percent of fuel use in the European Union compared to only 13 percent in the United States (PCA 2019a).

Around 40 percent of emissions from cement, or roughly 27 $MtCO_2$, come from the combustion of fuels (EPA 2020; Lehne and Preston 2018). Alternative fuels could reduce this, with the total abatement amount depending on a number of factors specific to the current fuel mix of a plant (data for which

Figure A1 | **U.S. cement plant locations and the opportunities to replace coal with carbon-dense solid biomass waste**



Notes: The map of cement plant locations is overlaid with carbon-dense waste biomass availability as an example of one potential replacement for coal based on comparable heating values and carbon densities. The potential of this approach is limited by total supply, regional variability, transportation logistics, and competition for other uses, but estimates based on availability indicate a potential emissions reduction of 2.7 million metric tons of carbon dioxide ($MtCO_2$) (Pisciotta et al. forthcoming).
Sources: Pisciotta et al. forthcoming. Based on data from EPA 2018 and USDA 2019.

is not publicly available), the availability of alternative fuels, and other plant-specific considerations.

More frontier options for fuel switching include hydrogen-fired or electric kilns, but both are still in development and require further investigation (Sandalow et al. 2019).

A.4 Novel Cements

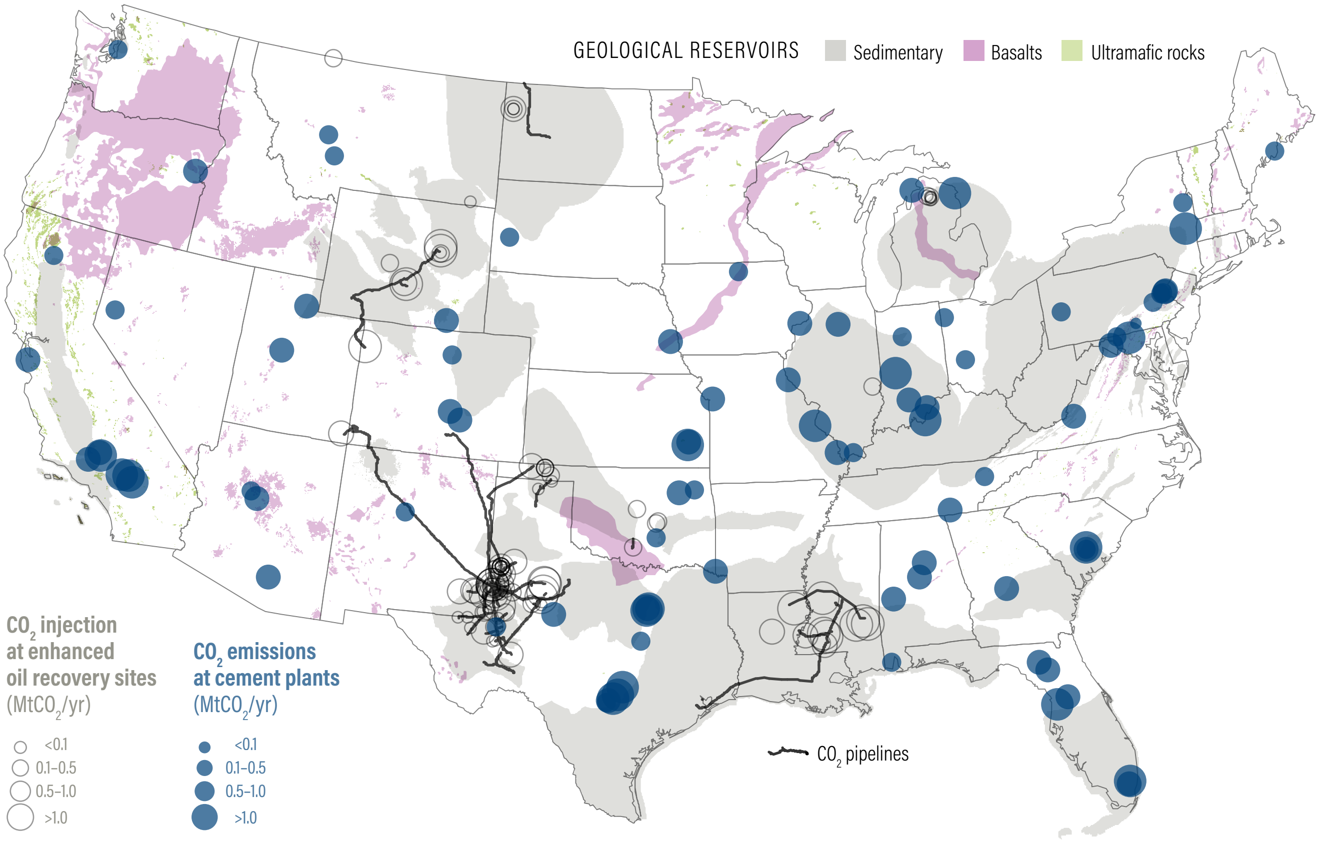
Novel cements are not based on portland cement combined with SCMs but are cements that rely on entirely new chemistries. A number of companies are working on such "alternative binders" that can replace portland cement using natural materials such as calcined clay and pozzolans or waste materials such as steel slag. These materials can reduce process emissions from 7 percent to 100 percent depending on the material used (Lehne and Preston 2018), and they may also reduce emissions from fuel combustion. Some are cured in a high CO_2 environment rather than with water, which currently limits their application to precast components but increases near-term carbon storage. Depending on the CO_2 source, this can contribute to CO_2 sequestration in the concrete and can reduce water usage.

Novel cements face a number of challenges. Many are in development and are not yet commercially available at any meaningful scale. In some cases, input materials are limited or more expensive, which limits the potential for scaling up. Buyers may be reluctant because industry specifications are based on existing and accepted forms of cement, and the use of new materials can be risky in an industry that prioritizes safety and durability.[6] Lastly, some types of concretes made with novel cements have limitations on their use—for example, some are only available as precast elements rather than as ready-mix—and may take longer to gain strength, a key metric in construction projects.

A.5 Carbon Capture, Use, and Storage

CCUS can theoretically capture the vast majority of cement plant emissions because process and fuel combustion emissions leave the kiln through a single smokestack to which a CCUS system could be retrofitted. This is in contrast with other industrial facilities that often have more than one smokestack. It can also capture both process and fuel combustion emissions, whereas most abatement options just impact one of those. If a 90 percent capture rate of kiln flue gas is assumed (as reported by Svante [2020], a

Figure A2 | **Map of U.S. cement plants with scale of CO_2 emissions for potential abatement with CCUS**



Notes: The map of U.S. cement plant locations is overlaid with existing carbon dioxide (CO_2) pipelines and potential opportunities for geologic storage or enhanced oil recovery with captured CO_2.
Source: Pisciotta et al. forthcoming. Based on data from EPA 2018, Hart Energy Publishing 2014, Hartmann and Moosdorf 2012, Johansson et al. 2018, and USGS 2013.

company developing CCUS systems for industrial emitters), up to 60 $MtCO_2$ could be captured annually, assuming the energy used to capture the CO_2 is carbon free (which may be difficult in some cases).

Carbon capture would not make sense for all cement plants and would depend on the remaining kiln lifetime, the capital and operating costs, and the expected emissions avoided. In some cases, less costly options—such as fuel switching or reducing the clinker-to-cement ratio—may be more applicable in the near term. Once the CO_2 is captured, it would need to either be used in close proximity to the plant or transported via pipeline or truck to another location for use or storage, so proximity to CO_2 pipelines would make this approach more favorable (Figure A2).

CCUS systems on cement plants are not yet deployed at commercial scale, though a handful of large- and commercial-scale projects are under development around the world (IEA 2020a). Although most decarbonization pathways rely heavily on CCUS, there are significant barriers to large-scale deployment, most prominently high capital and operating costs. Other barriers include permitting; higher energy demand to power the system; low CO_2 concentrations in flue gas relative to other industries; the need to pretreat flue gas to remove particulate matter, sulfur oxides, nitrogen oxides, and oxygen in some cases; and the need for infrastructure to move captured CO_2 to sites of storage or use. Complementary innovation and technical support policies will be needed to address these technical and market barriers.

A.6 Oxy-combustion

Oxy-combustion involves combustion of fuel in a high oxygen environment rather than air, resulting in an exhaust stream of pure CO_2 and water, where CO_2 can easily be captured and separated by condensation. In this way, oxy-combustion could yield 100 percent capture of CO_2 in flue gas. Net carbon captured would be lower, considering offsetting emissions from the materials and infrastructure needed for the process. Oxy-combustion for cement plants has not been well studied yet. There has been limited modeling and one small-scale pilot test thus far; additional research is required on its application to commercial-scale cement plants (Ditaranto and Bakken 2019). If available for a commercial-scale plant, it would require an oxygen producer nearby to be cost-effective and would likely require a specialized kiln for maximum efficiency. It would also require CO_2 transport infrastructure or a way to use captured CO_2 on-site.

APPENDIX B: DECARBONIZATION OPPORTUNITIES FOR CONCRETE

Although this paper focuses on a low-carbon cement standard and the abatement options that can reduce the emissions associated with the production of cement, the following sections are included to provide context on additional approaches to reduce the carbon intensity of concrete, the final product for the majority of cement in the United States. With the right combination of abatement options applied at both the cement and concrete plants, it would be possible to produce carbon-negative concrete.

B.1 The Ratio of Cement to Concrete

This approach is similar to reducing the amount of clinker in cement, but the SCM substitution happens at the concrete plant. SCMs include industrial wastes, such as fly ash and steel slag, as well as natural materials, including calcined clay and natural pozzolans, which confer cementitious properties to the concrete. They may provide other benefits, such as reducing the heat of hydration or water use, but can sometimes take longer to contribute to strength gain, limiting their applicability for some of concrete's end uses (Hanson 2017).

In the United States, unlike in other countries, SCMs are generally added at the concrete plant rather than at the cement plant, so incentivizing this approach may be more successful than incentivizing substitutions in cement. Even so, the scaled-up use of SCMs depends on the availability of suitable materials, which is limited and geographically variable; the end use of the concrete, which may require certain strength levels that cannot be achieved with high SCM content; and consumer demand, among others.

B.2 Aggregate

The use of recycled aggregate can reduce concrete's embodied carbon by avoiding emissions associated with the quarrying and transport of rock and sand. Although these emissions are relatively low—around 15 percent of the total for concrete (Gregory 2019)—recycled aggregate may also reduce the negative environmental and social impacts related to extraction. Recycled aggregate is generally sourced from old concrete; thus, some contractors may be reluctant to use it if the exact composition is unknown, and in some cases it may not be as strong as virgin aggregate, leading to an increased use of cement that offsets the recycled aggregate's abatement.

Synthetic aggregate is another option that could reduce the carbon footprint of concrete. It involves reacting CO_2 with alkaline minerals to form synthetic materials used in place of natural aggregate. The extent of emissions reduction of this approach depends on the level of emissions associated with the production process; more work on comprehensive life cycle assessments is needed to better understand the net carbon impact. The long-term scalability of synthetic aggregate will likely be constrained by access to suitable mineral feedstocks at large scales. There would also be costs associated with where and how the CO_2 is sourced as well as how it is transported. The long-term durability of synthetic aggregate also needs to be better understood. Companies such as Blue Planet in the United States and Carbon8 Aggregates in the United Kingdom are working on this option.

B.3 CO_2 Curing

Cement and aggregates generally use water to drive the reactions that result in hardening, or curing, into the final product, concrete. However, CO_2 can be used in addition to water to cure conventional portland cement as well as some novel cements. Ready-mix concrete can be injected with small amounts of CO_2 that mineralizes, and precast concrete elements can be cured in high CO_2 environments. CO_2 curing may help increase the strength of the concrete, requiring less cement and thus decreasing its carbon intensity and could also serve as a means to store captured CO_2. The net emissions impact of this approach and its effect on strength depend on a number of factors and require further life cycle assessment analysis (Ravikumar et al. 2021).

ABBREVIATIONS

CCUS	carbon capture, use, and storage
CH_4	methane
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
EGU	electric generating units
EPD	environmental product declaration
GHG	greenhouse gas
Gt	billion metric tons
IEA	International Energy Agency
LCFS	Low-Carbon Fuel Standard
Mt	million metric tons
N_2O	nitrous oxide
RD&D	research, development, and demonstration
SCM	supplementary cementitious material
SDS	Sustainable Development Scenario
WTO	World Trade Organization

ENDNOTES

1. The IEA's SDS holds temperature rise to 1.8°C with a 66 percent probability. Within the SDS, CO_2 emissions from energy and industrial processes fall from 36 $GtCO_2$ in 2019 to less than 10 $GtCO_2$ in 2050 and to net-zero emissions by 2070 (IEA 2020a).
2. Calculated based on the U.S. Energy Information Administration's figures for overall CO_2 intensity of electricity generation in 2019 (EIA 2020b).
3. The details of how to apply the standard to imports would need to be carefully designed to comply with World Trade Organization (WTO) rules. King et al. (2020) includes some discussion of how WTO rules can affect the design of a clean product standard.
4. See, for example, the discussion regarding electric generating units (EGUs) in Nordhaus and Gutherz (2014). There are significant differences between the use of Section 111(d) for cement plants as compared with EGUs, but this provides an overview of a number of the primary potential legal hurdles.
5. The ASTM sets standards for a wide range of materials and processes, and AASHTO sets highway design and construction standards.
6. In 2017, the ASTM established a subcommittee to focus on creating standards for nonhydraulic cements.

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ACKNOWLEDGMENTS

The authors are grateful to numerous individuals who provided valuable input, feedback, and support to this work. We thank our external reviewers who have shared their expertise and insights: Rebecca Dell, Derick Dreyer, Heather Dylla, Bob Epstein, Jed Ela, Charles Franklin, Jeremy Gregory, Rory Jacobson, Meghan Lewis, Colin McCormick, Michael Nixon, Hélène Pilorgé, Jessie Stolark, Tom Tietz, and Eric Trusciewicz. We would especially like to thank Hélène Pilorgé for her work developing the maps showing the opportunity for biomass waste substitution and CCUS.

Thanks also goes to WRI colleagues for their thoughtful review, comments, insights, and guidance: Zachary Byrum, Tom Cyrs, Joel Jaeger, Dayuma Ruiz, and Jen Wilcox. We would especially like to thank Dan Lashof for his review and guidance.

While the contributions from reviewers are greatly appreciated, the views presented in this paper reflect those of the authors alone.

We also wish to thank Romain Warnault, Emily Matthews, Lauri Scherer, Emilia Suarez, and Carni Klirs for editing, design, and production, and Matt Herbert for communications support.

This project was made possible through the generous funding of Gates Ventures and Breakthrough Energy.

Breakthrough Energy

ABOUT THE AUTHORS

Taryn Fransen is a Senior Fellow in the Global Climate Program at WRI, where she leads work on how countries can strengthen their commitments under the Paris Agreement.

Contact: taryn.fransen@wri.org

Katie Lebling is an Associate in the U.S. Climate Program at WRI. Her work focuses on policy options to scale up technological carbon removal solutions in the United States.

Contact: katie.lebling@wri.org

Debbie Weyl is Deputy Director of WRI United States, where she helps coordinate WRI's work in the United States across climate, energy, forests, business, economics, and sustainable cities programs.

Contact: debbie.weyl@wri.org

Kevin Kennedy is a Senior Fellow in the U.S. Climate Initiative at WRI, where he leads work on market-based climate policies and on subnational climate action.

Contact: kevin.kennedy@wri.org

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World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

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Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision

We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach

COUNT IT

We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT

We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

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We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.