Recasting the Future: Policy Approaches to Drive Cement Decarbonization

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Report prepared by Synapse Energy Economics, Inc.
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CATF CLEAN AIR TASK FORCE

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Executive Summary

Cement is a crucial element of infrastructure development and economic vitality in the United States. Production of cement in the United States employs approximately 14,000 workers and generates 91 million metric tons of cement annually. However, the cement manufacturing process is responsible for a substantial share of greenhouse gas (GHG) emissions: 71.3 million metric tons annually or 4.4 percent of U.S. total industrial emissions and 1.1 percent of total gross U.S. GHG emissions. To support reducing GHG emissions while preserving economic growth and infrastructure resilience, this whitepaper presents key technological pathways, adoption strategies, and policy recommendations for transitioning to a low-carbon cement industry.

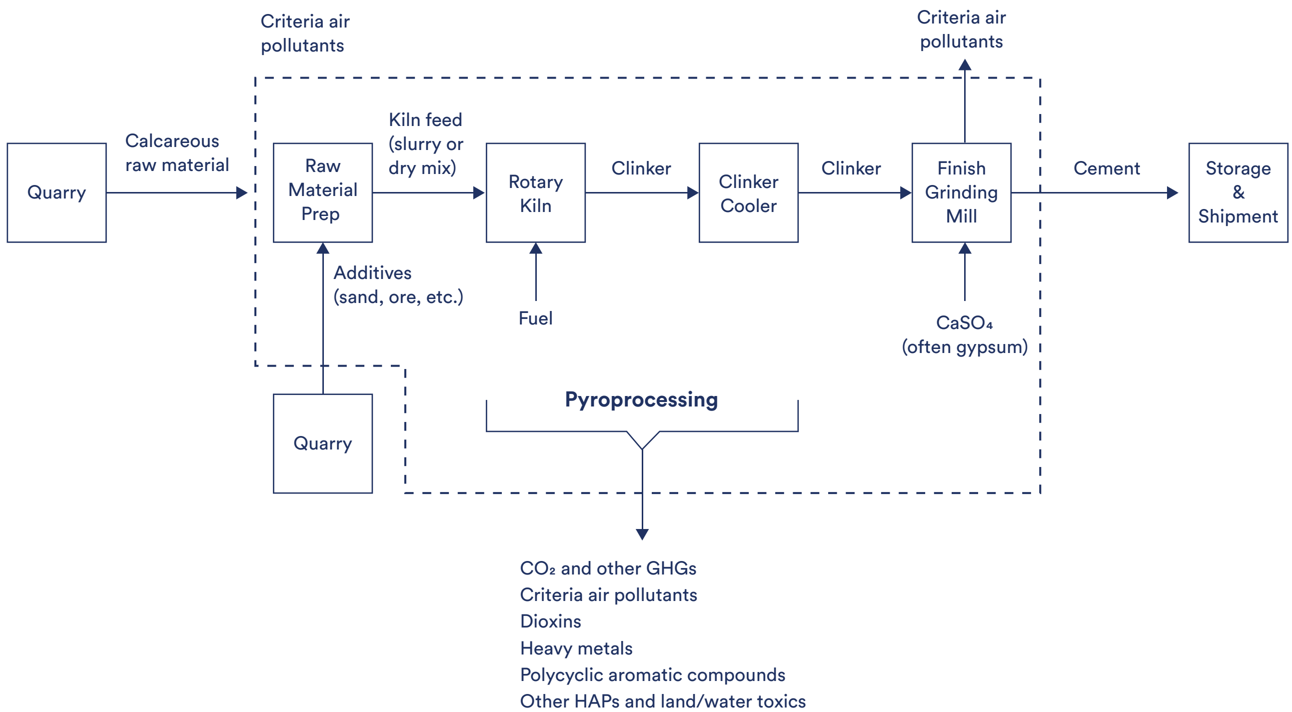
Cement Sector Overview

The U.S. cement industry consists of 92 manufacturing plants, which have become more efficient over time through conversion to dry production processes and reuse of waste heat from fuel combustion. The remaining efficiency gains available to the industry are relatively limited, as kilns with outdated production technology represent only 7.3 percent of the 2019 kiln capacity in the United States. **Figure ES-1** illustrates the key stages of cement manufacturing, emphasizing the processes responsible for GHG emissions and other pollutants. Cement plants release 140 different regulated pollutants into air, land, and water, and particulate emissions from cement production are responsible for hundreds of premature deaths annually in the United States, among other adverse health impacts.

Over time, the cement sector has undergone a transition from coal to natural gas, as demonstrated in **Table ES-1**. Despite this shift, many of the largest and most recently constructed kilns still use coal or coke as their primary fuel (**Figure ES-2**). Because coal typically costs less than natural gas on a dollars per MMBtu basis in the industrial sector, the economic incentives for fuel-switching from coal to gas at cement kilns depend on the characteristics of local fuel markets and infrastructure availability, rather than a universal advantage of one fuel over the other. Existing cement kilns that burn coal or coke are priority candidates for GHG emission control technologies such as carbon capture, utilization, and storage (CCUS), both because these plants are currently high emitters and because CCUS generally has a lower cost per ton of carbon captured at facilities with higher concentrations of carbon dioxide (CO_2) in their exhaust streams.

While fuel combustion is a key source of GHG emissions, nearly 60 percent of the emissions from cement-making are non-energy-related and result from the calcination process, which releases carbon from limestone. Importantly, because these process emissions result from chemical reactions involved in cement production rather than fuel combustion, the industry cannot abate them through fuel-switching.

Figure ES-1: Cement production process diagram



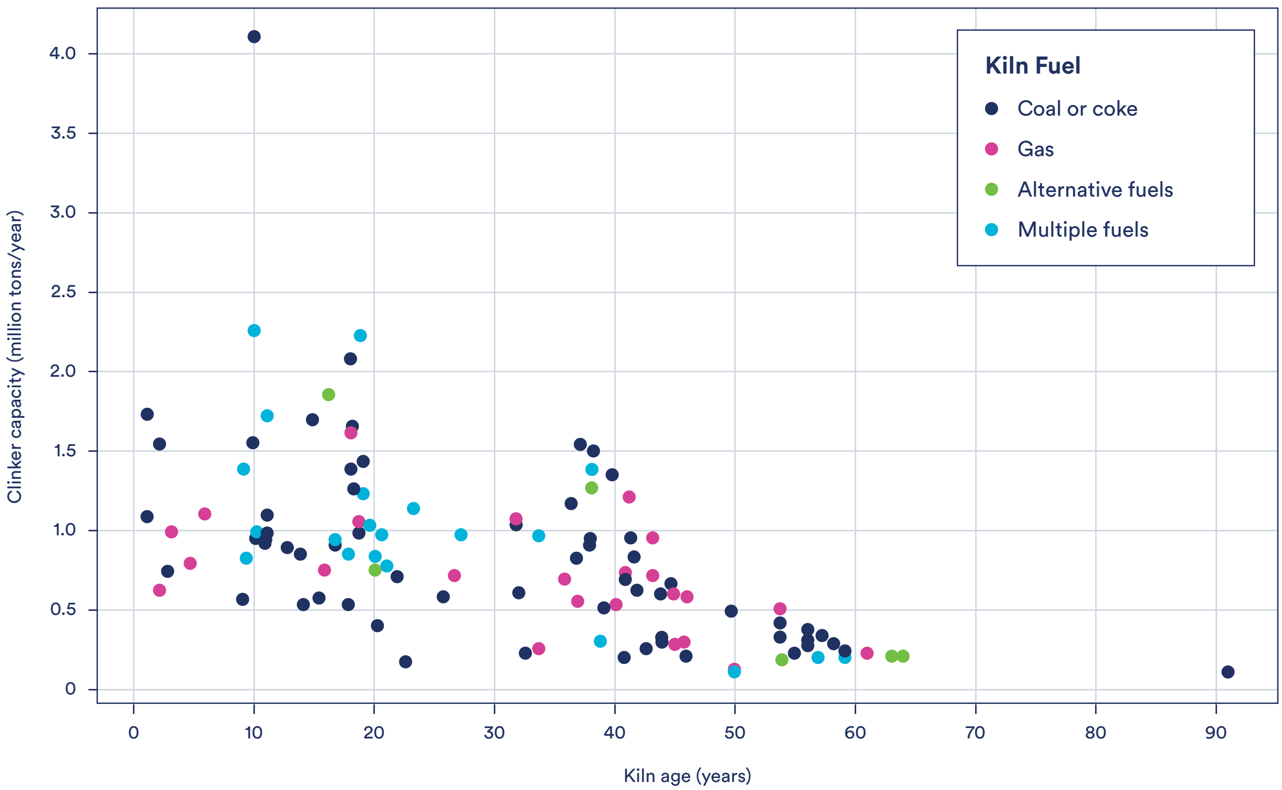
Notes: The dotted line shows the boundary of the facilities that we categorize as Scope 1 in this report.

Table ES-1: Fuel consumption by U.S. cement plants in 2000 and 2022

Category	Fuel	Energy Consumption (TBtu)		Share of Total Energy Consumption(%)	
Scope 1: Conventional fuels	Coal Petcoke Oil Natural gas	214.7 49.0 4.57 12.3	100.6 50.8 1.25 77.5	57.4% 13.1% 1.2% 3.3%	31.5% 15.9% 0.4% 24.2%
Scope 1: Waste fuels	Tires Solid waste Liquid waste	11.2 11.6 29.5	12.3 12.8 24.5	3.0% 3.1% 7.9%	3.8% 4.0% 7.7%
Scope 2	Purchased electricity	41.0	39.9	11.0%	12.5%
Total	**All**	**373.9**	**319.8**	**100%**	**100%**

Source: USGS. (2024). "Cement 2022 tables-only release." Minerals Yearbook 2022, v. I, Metals and Minerals. Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information; USGS. "Cement Minerals Yearbook 2000." Available at https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/mineral-pubs/cement/170400.pdf.

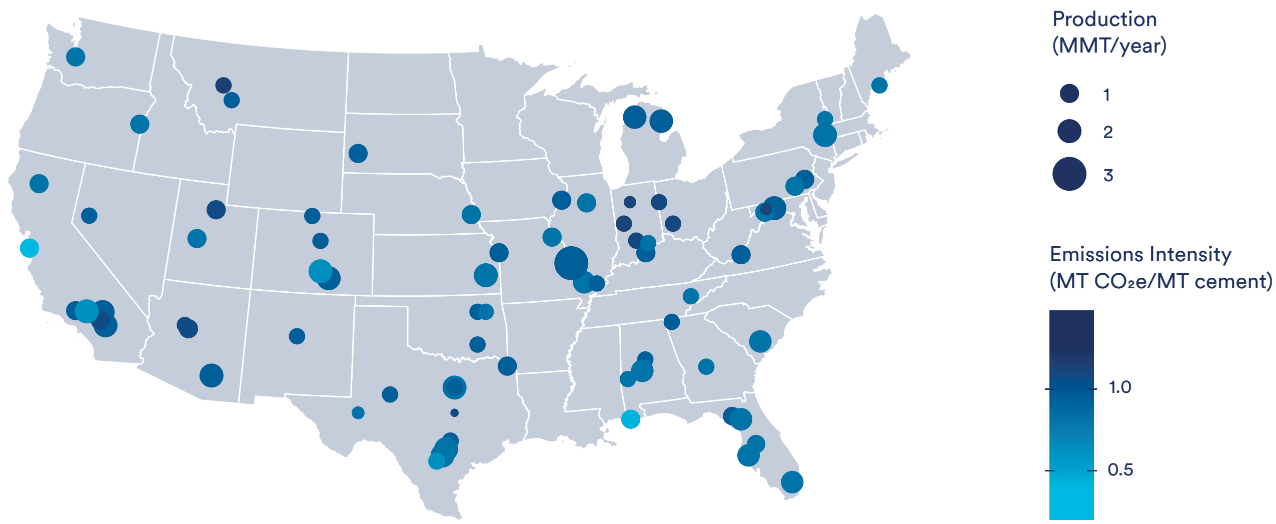
Figure ES-2: Summary of U.S. cement kiln capacity, age, and fuel in 2019



Source: Portland Cement Association. (2021). U.S. Portland Cement Industry: Plant Information Summary. Includes data through December 31, 2019.

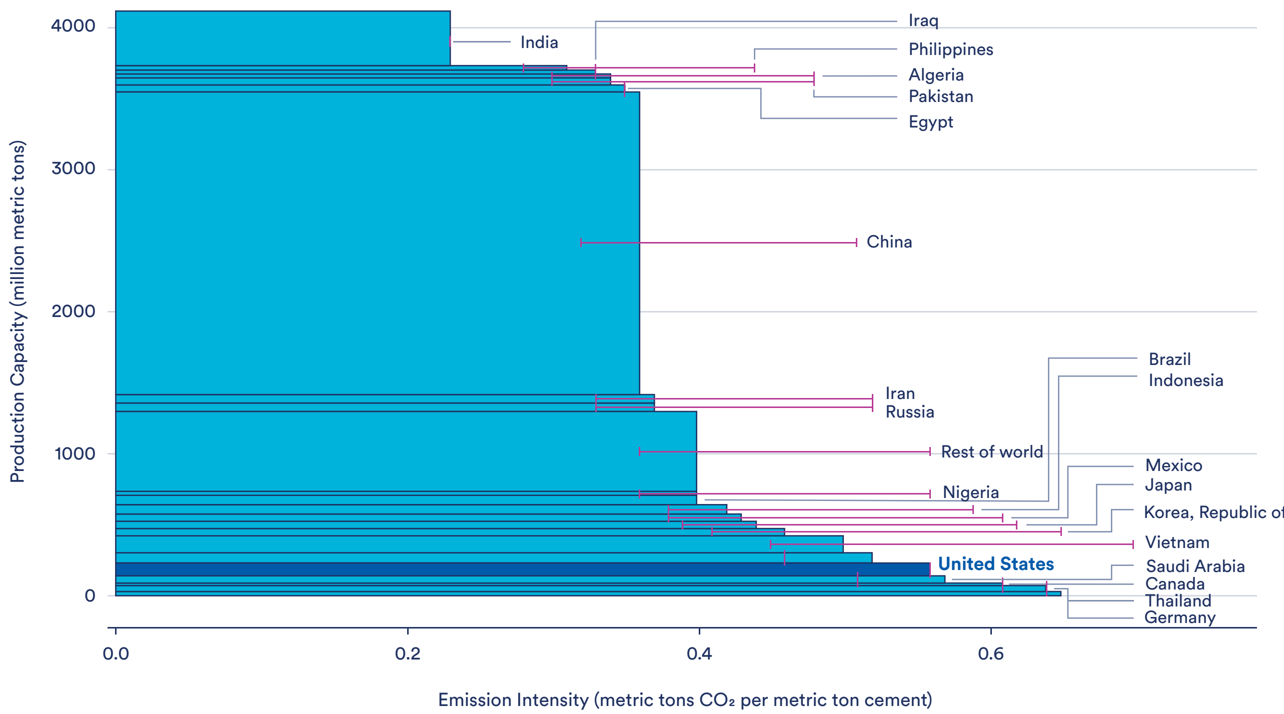
Emissions from cement production vary regionally, as shown in **Figure ES-3**, which showcases locations where targeted early interventions may be most impactful. However, because cement production is highly regionalized due to the weight and transport costs of raw materials, deep sectoral decarbonization will require targeting facilities throughout the United States. Compared to global markets, U.S. cement production remains more emissions-intensive (**Figure ES-4**). This underscores the urgency for policy interventions to spur decarbonization.

Figure ES-3: Map of facility-level production capacity (point size) and Scopes 1 and 2 emissions intensity (color)



Source: Synapse Energy Economics. (2023). "Coming Clean on Industrial Emissions: Final Database 2023-06." Prepared for Sierra Club. Available at: https://www.sierraclub.org/articles/2023/09/overview-coming-clean-industrial-emissions-report. Darker blue indicates higher emissions intensity. Larger point size indicates higher production capacity.

Figure ES-4: Comparison of U.S. cement emission intensity to global supply



Source: Synapse analysis of data from USGS, Global Carbon Budget, and GCCA. Excludes emissions from onsite power generation. Error bars indicate 95 percent confidence interval for countries that do not appear in the GCCA dataset. Note, GCCA and Global Carbon Budget emission accounting protocols differ from U.S. EPA data used elsewhere in this report, which may cause appearance of inconsistent results.

USGS. (2024). Cement Statistics and Information. Mineral yearbook 2022. Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information.

Our World in Data and Global Carbon Budget. (2024). Accessed October 16, 2024. Available at: https://ourworldindata.org/grapher/annual-co2-cement.

Global Cement and Concrete Association. (2024). "GNR 2.0 – GCCA in Numbers." Accessed December 19, 2024. Available by request at: https://gccassociation.org/sustainability-innovation/gnr-gcca-in-numbers/.

The U.S. cement industry is structured with a concentrated supply side dominated by a few multinational corporations. The demand side is heavily influenced by government procurement, which accounts for nearly half of total cement purchases. The supply chain is fragmented in the middle, with numerous intermediaries such as ready-mix concrete producers, wholesalers, and contractors. Despite this fragmentation, market concentration remains below regulatory thresholds and further consolidation is possible. Major companies such as Holcim and Heidelberg have pursued CCUS projects in Europe, but similar investments in the United States remain limited due to policy uncertainty and inadequate incentives.

On the demand side, the reliance on spot transactions and short-term procurement strategies makes it challenging for cement producers to secure low-cost financing for decarbonization projects. Unlike other industries that benefit from long-term off-take agreements, the cement sector largely operates on cyclical demand patterns tied to macroeconomic trends such as infrastructure spending and housing construction. Cement prices, which have seen substantial fluctuations, are driven more by demand-side changes than by supply constraints. While decarbonization measures such as CCUS could increase cement prices by 20–40 percent, their impact on overall construction costs would be minimal, emphasizing the need for market structures that support the financial viability of low-carbon cement production.

Technology Pathways to Decarbonize Cement Production

Several technological pathways exist to reduce emissions, including:

1. **Plant Efficiency Upgrades:** Making cement plants more energy-efficient is one of the simplest ways to cut emissions. This includes upgrading kilns, improving heat recovery, and using better grinding equipment. Plant operators have already made the most cost-effective of these improvements, however, and the remaining potential emissions reductions based on current technologies is unlikely to exceed 8 percent. These upgrades are widely used today and are **ready for full deployment.**
2. **Alternative Feedstocks and Production Processes:** Traditional cement relies on limestone, which releases a large amount of CO_2 when processed. Using alternative raw materials such as certain types of rock, industrial waste, or mining leftovers can reduce these emissions. New production methods, such as using electricity instead of fossil fuels for heating, could also help. Some companies are building pilot plants to test these methods, and they could be **market-ready within a few years**.
3. **Clinker Substitution and Alternative Binder Chemistries:** Cement's key ingredient, clinker, is responsible for most of its emissions. By mixing in other materials such as limestone, fly ash (from coal plants), or industrial byproducts, producers can use less clinker while maintaining quality. Some of these substitutions are already common, while newer blends could cut emissions even further. Simple substitutions are **fully ready**, while newer blends are **still being tested**.
4. **Carbon Capture, Utilization, and Sequestration:** Technologies exist to capture CO_2 emissions from cement plants and store them underground or use them in other products. Some large-scale projects are already underway in Europe, but widespread adoption is still limited due to high costs and the need for better infrastructure. These systems are **close to commercial scale but still need more investment and incentives**.
5. **Alternative Fuels:** Cement plants traditionally burn coal or petroleum coke for energy, but they could use alternatives such as biomass, industrial waste, or even hydrogen. Some plants already use waste fuels, though their impact is limited. Hydrogen could play a role in the future, but it requires major infrastructure changes. Waste fuels and biomass are **already in use**, while hydrogen is **still in early stages**.
6. **Decarbonized Electricity:** Instead of burning fossil fuels, some new technologies aim to use electricity from renewable sources to power cement production. While some electric heating methods have been tested, fully electric cement plants are still in the early stages of development. If successful, this approach could greatly cut emissions. Some parts of the process are **almost ready**, while others **need more research**.
7. **Biocement:** Researchers are developing novel production methods to make cement using bacteria or other biological processes. These approaches could eliminate emissions from traditional heating and chemical reactions. So far, this technology has only been used for small-scale projects, and it is unclear how well they will scale up. This technology is in **early research and development**.
8. **Concrete Recarbonation and Circularity:** Once cement is used in buildings and roads, it naturally absorbs CO_2 from the air over time. Several companies are developing approaches to accelerate this process or inject captured CO_2 into fresh concrete, locking it in permanently. Some methods are **already in use** in construction, while others **still need further testing**.
9. **Concrete End-Use Design Optimization and Construction Site Efficiencies:** Improved construction techniques can reduce the overall demand for cement by using it more efficiently. Approaches include better design, using recycled materials, and extending the life of buildings. These approaches depend on architects,

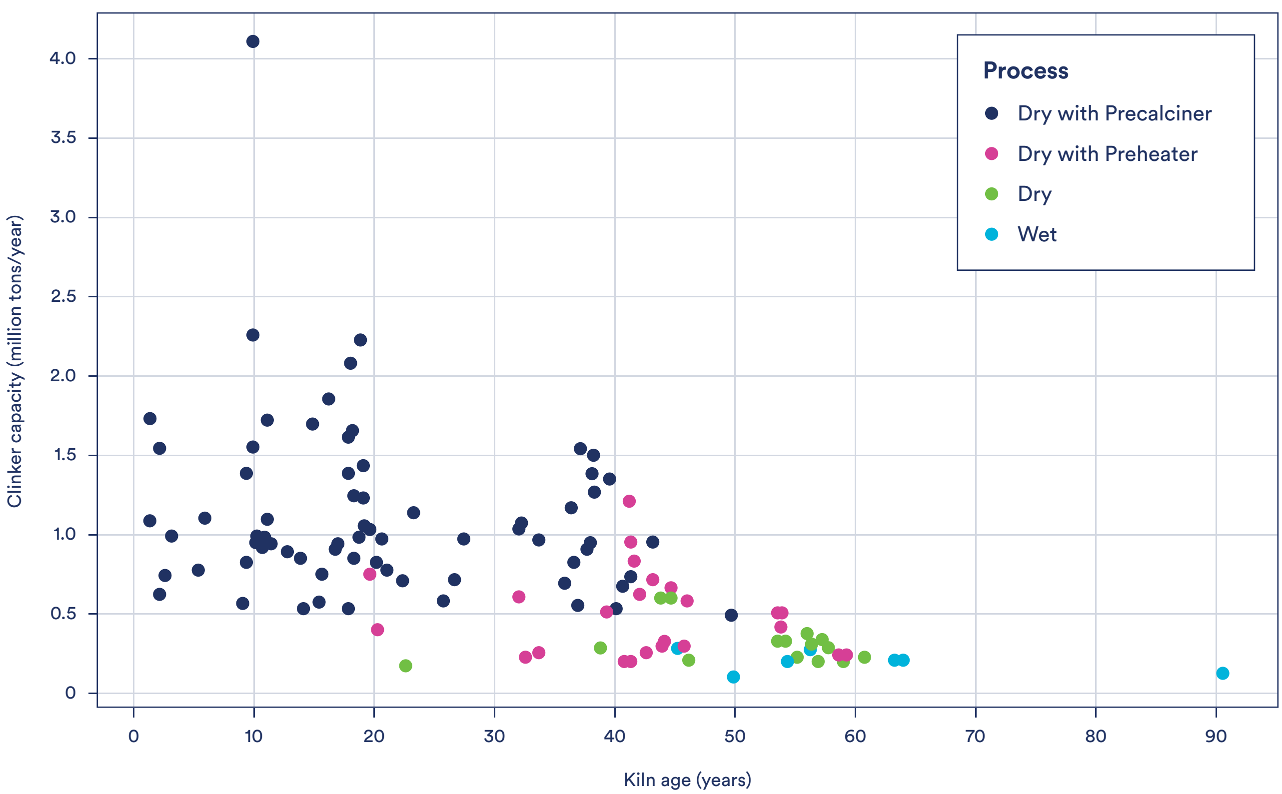
engineers, and construction firms adopting more efficient building techniques. Improved construction techniques could cut emissions by over 20 percent by 2050. Since these techniques rely on existing construction knowledge, they are **ready for adoption today**.

U.S. cement kiln capacity, age, and process type (**Figure ES-5**) provide insights into the industry's ability to adopt these technologies, with newer kilns better-suited for retrofit technologies such as CCUS to reduce their GHG emissions. Older cement kilns that use less efficient production processes are likely to be approaching the end of their useful lives and it is not economically viable to invest in capital-intensive pollution control retrofits for these kilns. Instead, these older kilns should be replaced at end-of-life with kilns that use newer low- or zero-carbon production methods.

Adoption Strategies

The U.S. cement sector's path to net-zero emissions by 2050 requires a coordinated policy portfolio integrating **financial support, market-based approaches,** and **regulatory interventions** to address technical, economic, and infrastructural barriers. Together, these strategies create a reinforcing cycle: public funding bridges innovation gaps, market incentives align producer and consumer interests, and regulations ensure compliance while mitigating carbon leakage. This triad of interventions—targeted across the technology lifecycle from R&D to commercialization—enables scalable decarbonization without sacrificing competitiveness. These solutions leverage cross-sector collaboration and infrastructure investments to lock in emissions reductions across regional production clusters.

Figure ES-5: Summary of U.S. cement kiln capacity, age, and process in 2019



Source: Portland Cement Association. (2021). U.S. Portland Cement Industry: Plant Information Summary. Includes data through December 31, 2019.

Financial Support

Financial mechanisms such as research, development, and deployment funding and pilot project grants de-risk early-stage technologies (e.g., biocement, CCUS retrofits). **Figure ES-6** below provides further details and considerations for available financial support strategies.

Figure ES-6: Financial support strategies for U.S. cement industry emissions reductions

Strategy	Description	Benefit	Design Considerations	Policy Gaps/ Barriers	Risks
Targeted Support for Low Technology-Readiness Level Technologies	Direct funding for early-stage technologies like biocement, electrochemical calcination, and hydrogen-fueled kilns to advance them from lab-scale to pilot-ready stages.	Accelerates innovation in breakthrough technologies that could achieve near-zero emissions in cement production.	Grants prioritized for technologies with high emissions reduction potential (e.g., greater than 50 percent reduction).	High research and development costs, investor risk aversion, and lack of scalable prototypes.	Potential failure to commercialize; competition from entrenched fossil-based processes.
Pilot and Demonstration Project Funding	Public-private partnerships to de-risk first-of-a-kind projects (e.g., CCUS retrofits, alternative feedstock plants).	De-risks commercialization of key decarbonization pathways, attracting private sector investment.	Mandate equity-sharing (e.g., 50 percent industry cost-matching) and emissions monitoring.	Long permitting timelines, supply chain gaps for novel materials.	Cost overruns; underperformance of unproven technologies; failure to commercialize.
Policy and Regulatory Support for CCUS Deployment	Streamlined permitting for CO_2 pipelines and storage, expanded 45Q tax credits, and federal liability coverage for sequestration.	Enables large-scale carbon capture at existing plants, reducing emissions from both combustion and calcination processes.	Index 45Q credits to inflation; extend eligibility to smaller facilities (less than 50,000 MT CO_2 per year).	Public opposition to CO_2 pipelines; slow Class VI well approvals (24+ months).	Leakage liability; reliance on fossil-fueled plants for cost-effective capture; limited opportunity for cost reduction compared to alternative feedstocks and production processes.

Market-Based Approaches

Market-based tools such as carbon advantage tariffs and advance procurement commitments stimulate demand for low-carbon products through price signals and guaranteed markets. **Figure ES-7** provides further details and considerations for available market-based strategies.

Figure ES-7: Market-based strategies for U.S. cement industry emissions reduction

Strategy	Description	Benefit	Design Considerations	Policy Gaps/ Barriers	Risks
Transparent and Verifiable Third-Party Labeling	Fostering a market for low-carbon cement through Environmental Product Declarations (EPDs) that are product-specific and based on verifiable data.	Builds market trust in low-carbon products, driving demand for low-carbon cement.	Align with ISO 14025 standards; regionalize low-carbon cement thresholds to account for feedstock variability.	Lack of standardized EPD methodologies; slow adoption by small producers.	Expertise to produce a product-specific EPD requires workforce training and technical assistance; market fragmentation from inconsistent state and federal criteria.
Advance Market Commitments	Federal procurement guarantees to purchase low-carbon cement at premium prices.	De-risks market entry for low-carbon cement manufacturers by guaranteeing demand at scale.	Tie funding commitments to technology readiness (e.g., limit contracts for near-commercialized technologies to 10 years).	Budget uncertainty related to unknown production volumes; resistance from contractors reliant on traditional materials.	Over-reliance on a few producers; price volatility if demand outpaces supply.
Clean Cement Buyers Association	Coalition of private and public purchasers (e.g., ConcreteZero) committing to procure cement with lower emissions intensity—(e.g., less than 0.6 tons CO_2e per ton cement by 2035).	Creates a unified market signal, encouraging producers to invest in lower-carbon production methods.	Tiered membership fees based on procurement volume.	Administrative startup challenges due to lack of U.S. participation in existing coalitions; time and effort to build consensus among buyers.	Limited supply of low-carbon cement could create mismatch with procurement commitments; setting emission standard at incorrect stringency would fail to effect change.

Strategy	Description	Benefit	Design Considerations	Policy Gaps/ Barriers	Risks
Government Procurement Models	Federal or state mandates requiring low-carbon cement in public projects.	Leverages government purchasing power to create stable, long-term demand for low-carbon cement, accelerating market transformation and investment in cleaner technologies.	Phase-in periods for proportion of cement that must be low carbon (e.g., 20 percent threshold by 2027, 40 percent by 2030).	Lack of regional low-carbon cement availability; could conflict with prescriptive ASTM standards.	Project delays if supply chains lag; setting procurement "strike" price too low would fail to effect change, but too high could incur unnecessary costs.
Carbon Advantage Tariff with Reinvestment	Border adjustment fees on imports exceeding U.S. emissions intensity, with revenue directed to domestic R&D.	Levels the playing field for domestic producers, discourages carbon leakage, and channels new resources into U.S. innovation and decarbonization efforts.	Align tariff rates with EU policy; exempt allies with comparable climate policies.	U.S. cement is more emissions-intensive than imported cement from top trade partners. **Cost:** $1.2 billion for monitoring/ enforcement infrastructure.	Increased construction costs; World Trade Organization compliance risks; retaliatory trade measures.

Regulatory Approaches

Regulatory measures, including binding low-carbon standards and performance-based specifications, enforce accountability and accelerate industry-wide adoption of cleaner practices. **Figure ES-8** provides further details and considerations for available regulatory strategies.

Figure ES-8: Regulatory strategies for U.S. cement industry emissions reduction

Strategy	Description	Benefit	Design Considerations	Policy Gaps/ Barriers	Risks
Low-Carbon Standards	Binding emissions thresholds for cement used in federally funded projects.	Drives sector-wide emissions reductions by setting clear, enforceable limits, which provide strong market signals for investment in low-carbon technologies.	Allow regional emissions intensity variation; clinker ratio and material composition flexibility; integration with procurement and EPD requirements; phased stringency and ratcheting.	Opposition from coal-dependent plants in Midwest and South.	Plant closures in regions lacking CCUS infrastructure; cost pass-through to consumers.

Strategy	Description	Benefit	Design Considerations	Policy Gaps/ Barriers	Risks
Construction Regulations	Updates to building codes (e.g., International Building Code) to favor low-carbon concrete in structural applications.	Encourages widespread adoption of low-carbon materials in the built environment, reducing lifecycle emissions from new construction and major renovations.	Exempt small-scale residential projects; address fragmented state/local code adoption with model codes and technical assistance; support contractor training and risk reduction; phase in requirements to allow industry adaptation.	Fragmented local code adoption; contractor lack of familiarity with new materials.	Slower project approvals; liability concerns over novel materials.
Performance-Based Material Standards	Replace prescriptive standards with outcome-focused criteria (e.g., compressive strength, durability) that can accommodate alternative feedstocks and production processes.	Unlocks innovation by allowing low-carbon cement blends and technologies to compete based on performance, not composition, accelerating market entry for advanced products.	Robust testing, validation, and workforce training; address risk aversion with pilot projects and data collection; provide sufficient lead time for industry adaptation.	Risk aversion among state transportation departments; lack of performance data for LC3 and blended cements.	Interim supply shortages during transition period.
Federal Air Regulations	Expand existing New Source Pollution Standards (NSPS) for new cement plants under Clean Air Act Section 111(b) to include CO_2 and a 111(d) standard for CO_2 emissions from existing cement plants.	Provides consistent, sector-wide emission standards; can serve as a policy backstop or a driver of more ambitious emissions reductions; can reduce harmful air co-pollutants and associated health impacts.	Differentiate standards for new vs. retrofitted plants; regulations can tighten over time as technological options for decarbonization improve.	Legal challenges from industry groups; increased operating costs for older kilns.	Premature retirement of plants unable to comply; job losses in fenceline communities.

Capital and Public Spending Requirements

The U.S. cement sector will need substantial capital and policy investments to decarbonize by 2050. Between $69 billion and $120 billion in cumulative capital expenditures are needed through 2050, primarily for new, alternative feedstock production facilities (e.g., electrochemical calcination) and for CCUS retrofits at existing plants. These investments aim to address the sector's reliance on coal- or coke-fueled kilns and high process emissions from limestone calcination, with CCUS retrofits prioritized for newer, more efficient plants.

A comprehensive suite of policies to support cement decarbonization could require $11.4 billion (2024$ with a zero percent discount rate) or $10.1 billion with a 2.15 percent federal discount rate, as shown in **Table ES-2**. These public funds must de-risk private sector investments, particularly for first-of-a-kind projects such as hydrogen-fueled kilns or LC3 (limestone calcined clay) cement plants, which face high upfront costs and uncertain returns.

Table ES-2: Public spending on cement decarbonization policies, 2026–2035 (2024$, million)

Approach	Total cost (0% discount rate)	Total cost (2.15% discount rate)
Research and Development	$76	$69
Pilot Projects	$3,885	$3,600
Increased tax credit (e.g., 45Q) for carbon capture	$2,729	$2,345
Support CO_2 infrastructure buildout through CIFIA	$1,480w	$1,305
Clean Buyers Association	$8	$7
Government Procurement	$2,832	$2,464
Advance Market Commitment	$45	$39
Third Party Labeling	$20	$18
Low-Carbon Standard	$42	$37
Construction Regulation	$25	$22
Performance-Based Standard	$216	$195
Federal Air Regulations	$41	$36
Grand Total	**$11,399**	**$10,136**

Source: Discount rate of 2.15 percent based on an inflation-indexed 10-year treasury constant maturity rate—Board of Governors of the Federal Reserve System. (Accessed April 14, 2025). "H.15 Selected Interest Rates," available at: https://www.federalreserve.gov/releases/h15/.

Conclusions and Recommendations for Policymakers

Decarbonizing the U.S. cement sector by 2050 demands synchronized financial, market, and regulatory interventions. Near-term priorities include scaling CCUS at coal-dependent plants, accelerating demonstrations of alternative feedstocks (e.g., electrochemical calcination), and aligning federal and state procurement policies with verified EPDs. The included **Policy Matrix** ranks interventions by feasibility, cost, and emissions impact, and it identifies CCUS retrofits and alternative feedstock scaling as high-priority pathways requiring urgent public investment. Success hinges on bridging critical infrastructure gaps (e.g., CO_2 pipelines), workforce training for CCUS operations, and resolving permitting bottlenecks for novel technologies. Without rapid action, investments spurred by federal infrastructure programs such as the *Bipartisan Infrastructure Law and CHIPS Act* risk locking in high-emission production for decades, thereby undermining climate goals.

To achieve net-zero emissions by 2050, policymakers should prioritize the following actions, informed by the report's analysis of capital needs, stakeholder support, and policy risks:

1. Financial Intervention Recommendations

- **Expand Research, Development, and Deployment Funding**: Allocate **$4 billion by 2035** for research and development coupled with pilot and demonstration projects. Target lower-readiness technologies, such as emerging alternative production and feedstock processes. Prioritize grants with industry cost-sharing requirements to de-risk private investment.
- **Strengthen 45Q Tax Credits:** Index credits to inflation and extend eligibility to smaller facilities (less than 50,000 tons CO_2 per year) to incentivize CCUS adoption at regional plants.
- **Accelerate CCUS Infrastructure:** Direct an additional **$2 billion via an extension of the CIFIA program** to build shared CO_2 transport/storage networks near cement clusters in the Midwest and South, where coal-dependent plants are concentrated.

2. Market-Based Strategy Recommendations

- **Advance Market Commitments:** Leverage the U.S. General Service Administration's (GSA) **$2.15 billion low-carbon materials fund** to guarantee 10-year procurement contracts for cement meeting less than 0.6 tons CO_2e per ton cement thresholds by 2035.
- **Clean Cement Buyers Association:** Launch a federal-state-private coalition to pool procurement demand, offering tiered membership incentives for contractors committing to low-carbon materials.

3. Regulatory Lever Recommendations

- **Federal Low-Carbon Standards:** Enforce binding emissions thresholds (e.g., less than or equal to 0.75 tons CO_2e per ton cement by 2030) for federally funded projects, with grandfathering provisions for plants transitioning to CCUS.
- **Performance-Based Specifications:** Replace the prescriptive ASTM C-150 Standard with outcome-focused criteria (e.g., compressive strength) by 2028, validated through Federal Highway Administration's Mobile Concrete Technology Center.
- **Fast-Track Permitting:** Pre-approve CO_2 pipeline corridors in priority states such as Texas, Indiana, and California and streamline Class VI well approvals to less than 18 months to avoid project delays.

4. Workforce and Equity Measure Recommendations

- **Fund Regional Training Programs:** Allocate funds forpartnerships between unions, community colleges, and manufacturers to upskill workers in CCUS operation and low-carbon cement production.
- **Prioritize Local Community Benefits:** Mandate community benefit agreements for CCUS projects in disadvantaged areas, ensuring local hiring and air quality monitoring.

Recommended Implementation Roadmap

Figure ES-9 below shows a potential timeline for when the above actions should be complete in order to achieve net-zero emissions for the U.S. cement industry by 2050.

The **Policy Matrix** on the following pages provides a detailed ranking of interventions requiring early public investment to unlock private capital. Policymakers must balance feasibility, cost, and stakeholder alignment—particularly addressing opposition from coal-reliant regions—to avoid market fragmentation and ensure equitable progress.

Table ES-9: Recommended deadlines for a decarbonized U.S. cement industry

2028	2035	2050
Finalize low-carbon procurement mandates (e.g., 0.6 tons CO_2e per ton cement), deploy support for three regional CCUS infrastructure hubs, and publish updated material performance standards for concrete.	Achieve 40 percent emissions reduction sector-wide via CCUS retrofits and alternative feedstock and production process scaling.	Transition remaining fossil-fuel-dependent plants to net-zero production methods and CCUS, supported by a skilled workforce and mature CO_2 transport and storage network.

Policy Matrix

Research Development and Demonstration Intervention Approach

	Intervention	Description	Target Technology Pathwyas	Implementaton Framework	Probability of Success
Financial	Target support for low TRL technologies	Federal funding for national and university materials labs researching technologies that are at early stages of development, including fostering partnerships among academic, industry, and government researchers.	All pathways	Primarily federal and state (e.g. through state universities) implementation; DOE can fund research and development with existing money appropriated to it; expanding this funding would require legislation.	• **Scale of Impact:** Small initial impact with potential for larger, longer-term impact • **Timeline:** Near-term adoption; medium- to long-term impact • **Stakeholder Position:** Opposition unlikely • **Risks:** Impact depends on adequate investment; not all technologies will succeed; geo-strategic risk if new technologies are commercialized abroad • **Alignment:** Provides foundational support to other policy initiatives • **Economic co-benefits:** Long-term potential for new jobs; helps maintain global competitiveness of U.S. cement industry
Financial	Pilot project funding	Federal funding for demonstration projects piloting new low-carbon cement technologies, e.g., DOE's Industrial Demonstrations Program.	Alternative feedstocks, alternative production processes, CCUS, alternative fuels, decarbonized electricity, bio-cement	Historically federal funding, though states could fund; DOE can support some projects with existing money appropriated to it; expanding this funding would require legislation. Medium cost; potential to leverage private sector funds through industry partnerships.	• **Scale of Impact:** Medium • **Timeline:** Near-term adoption, medium-term impact • **Stakeholder Position:** Opposition unlikely • **Risks:** Not all technologies will succeed; geo-strategic risk if new technologies are commercialized abroad • **Alignment:** Provides foundational support to other policy initiatives • **Economic co-benefits:** Long-term potential for new jobs; helps maintain global competitiveness of U.S. cement industry

Column Definitions:

Intervention Approach: Classification of the policy or regulation based on temporal stages for developing technological pathways and advancing them to market; mimics CATF Innovation Technology Framework.

Category: Type of intervention (market-based, regulatory, financial incentives).

Intervention: Policy or regulation aimed at reducing carbon emissions in cement manufacturing.

Description: Brief explanation of the intervention with any relevant examples.

Target Technology Pathways: technologies that would see increased adoption due to the intervention.

Implementation framework: Pathway to adoption, including intervention costs. Intervention costs reflect financial burden or investment required for implementation (e.g., High, Medium, Low). Focused only on programmatic and administrative costs for the intervention, not investments in infrastructure from industry.

Probability of Success: Likelihood of achieving decarbonization goals, informed by listed factors:

- **Time Horizon for Impact:** The expected timeframe for the policy to achieve its intended decarbonization impact (e.g., Near-Term (1-5 years), Medium-Term (5-10 years), Long-Term (>10 years)).
- **Risk of Unintended Consequences:** The potential for the policy to have negative or counterproductive effects (e.g., dislocation of emissions, market distortions, increased costs, reduced competitiveness).
- **Stakeholder Support/Opposition:** Level of support or opposition from key stakeholders such as industry, government, NGOs, EJ communities, and the public at large (e.g., Strong Support, Moderate Support, Opposition).
- **Economic Co-Benefits:** Other economic advantages generated by the policy, such as job creation, innovation stimulation, or industrial competitiveness (e.g., High, Medium, Low).
- **Alignment with Existing Policies:** How well the policy aligns with or complements existing state, national, or international climate policies and goals (e.g., Fully Aligned, Partially Aligned, Misaligned).

Commercialization Intervention Approach

	Intervention	Description	Target Technology Pathwyas	Implementaton Framework	Probability of Success
Market-Based	Advance market commitments	Government (federal, state, and local) and corporate off-take agreements for low-carbon alternatives, intended to de-risk financing for low-carbon concrete or cement; can include contracts for difference.	Alternative feedstocks, alternative production processes, clinker substitution, alternative binder chemistries, bio-cement	• Administrative or legislative decisions by federal, state, and local agencies or governance bodies • Authority may need to be granted • Low cost relative to overall construction cost • Corporate off-take agreements can expand implementation to the private sector	• **Scale of Impact:** High • **Timeline:** Near-term adoption, medium-term impact • **Stakeholder Position:** Incumbent opposition to "picking winners & losers" • **Risks:** Non-performance and delivery risks, technology risk • **Alignment:** Partially aligned; potential for overpayment if paired with supply-side policies
Market-Based	Government procurement models	Leveraging government purchasing power to increase demand for low-carbon concrete; examples include: • Contracts for differences (payment to contractor to account for bid differences between a low-carbon and traditional concrete) • Federal initiatives (Buy Clean, FHWA program, GSA fund) • Low-carbon concrete preferential bidding • Emission intensity thresholds for publicly procured cement	All pathways	Administrative or legislative decisions by federal, state, and local agencies or governance bodies; Authority may need to be granted; Low cost relative to overall construction cost.	• **Scale of Impact:** High • **Timeline:** Near-term adoption, medium-term impact • **Stakeholder Position:** Potential industry opposition • **Risks:** Limited • **Alignment:** Fully aligned
Financial	Policy and regulatory support for CCUS deployment	Incentivize and coordinate CCUS deployment, e.g., through enhanced 45Q tax credit for captured carbon, demonstration projects, financing support for large-scale CO_2 transport infrastructure, and streamlined permitting for CO_2 injection wells.	CCUS	• Federal (e.g., tax code) or possibly state (e.g., permitting) implementation • New legislation would be required to expand the existing federal CCUS credit; potentially high cost if adoption level is high • Other mechanisms such as streamlined permitting would be lower cost since they do not require ongoing payments	• **Scale of Impact:** Medium to high • **Timeline:** Near-term adoption, medium-term impact • **Stakeholder Position:** EJ opposition, especially from communities living near pipelines and injection wells • **Risks:** Low technological readiness, access to financing, community opposition to infrastructure siting, potential for perverse incentives • **Alignment:** Alignment depends on details of policy design

	Intervention	Description	Target Technology Pathwyas	Implementaton Framework	Probability of Success
Market-Based	Carbon advantage tariff with reinvestment	Carbon-based tariff on imported cement or concrete that is more carbon intensive than U.S. average; tariff revenues invested in decarbonization of domestic cement.	All pathways	• Federal implementation through congressional legislation (e.g., PROVE IT Act, Clean Competition Act, FAIR Transition & Competition Act, Foreign Pollution Fee Act) or Executive Branch action • Cost for federal action is primarily administrative; tariffs can cover the cost of new domestic investment	• **Scale of Impact:** Low because U.S. cement is carbon-intensive • **Timeline:** Near-term adoption, medium-term for tariff reinvestment to reduce emissions • **Stakeholder Position:** Support from cement industry; opposition from construction industry and public or advocates due to inflationary effects • **Risks:** Limited near-term effectiveness since U.S. cement is currently more carbon-intensive than most other countries • **Alignment:** Partially • **Economic Co-benefits:** Would encourage growth of domestic cement industry
Market-Based	Transparent and verifiable third-party labeling	Increase transparency in the carbon intensity of cement by developing environmental product declarations that provide information about the lifecycle GHG emissions associated with a given product; can be voluntary or regulatory.	All pathways	• Implementation by federal and state agencies, in partnership with industry • EPA is currently developing a voluntary low-embodied carbon labeling program for construction materials • State governments and cement trade groups could also develop labeling standards • Congressional action needed for mandatory labeling • Low- to moderate-costs associated with administration and verification	• **Scale of Impact:** High • **Timeline:** Near-term adoption and impact • **Stakeholder Position:** Opposition unlikely • **Risks:** Transparency and verification risks; impact depends on consumers preferentially selecting low-carbon cement once information is available • **Alignment:** Fully aligned; foundational for many other policies

Market Maturity Intervention Approach

	Intervention	Description	Target Technology Pathwyas	Implementaton Framework	Probability of Success
Regulation	Low-carbon standards	Adopt carbon intensity standards for concrete.	Plant efficiency upgrades, alternative feedstocks, alternative production processes, clinker substitution, alternative binder chemistries, CCUS, alternative fuels, decarbonized electricity, bio-cement	• Industry-wide through standards setting process or congressional legislation; possible pathways for statewide low-carbon standards, though states' legal authority to regulate may vary • Costs are primarily administrative	• **Scale of Impact:** Large, depending on stringency of carbon intensity standard • **Timeline:** Near-term adoption, near- to medium-term impact • **Stakeholder Position:** Industry opposition; possible client and practitioner opposition to potential costs • **Risks:** Misapplication could lead to structural failure; enforcement challenges • **Alignment:** Pairs well with carbon tariffs; requires transparent and verifiable third-party labeling
Regulation	Construction regulations	Requirements for the efficient use or re-use of concrete in construction projects, such as through building codes and construction specifications.	Recarbonation, concrete design optimization	• Standards, codes, and agencies (e.g., federal, state, and local transportation departments); incorporate in regular update cycle; low cost to adopt • Policy cost is low since there are no ongoing costs once the new standards are in place	• **Scale of Impact:** Large (up to 22% reduction) • **Timeline:** Medium-term adoption and impact • **Stakeholder Position:** Client and practitioner opposition due to perceived liability • **Risks:** Misapplication could lead to structural failure; enforcement challenges • **Alignment:** Aligned to market-based strategies
Market-Based	Clean cement buyers association	Establish a U.S.-based clean cement buyers association, targeted toward major federal/ state construction contractors, or increase U.S. participation in an existing international buyers association.	All pathways	• U.S. cement producers could join ConcreteZero (an existing international buyers association) or could coordinate to establish a new, U.S.-based association • Policy implementation cost would be low since the private sector would lead the effort	• **Scale of Impact:** Medium • **Timeline:** Near- to medium-term adoption; impact begins once associations are formed • **Stakeholder Position:** Opposition unlikely • **Risks:** Markets for low-carbon cement are currently immature; impact depends on the availability of low-carbon cement and off-taker willingness to pay a price premium • **Alignment:** Fully aligned; the development of a robust domestic buyers association would be complementary to other policy efforts

	Intervention	Description	Target Technology Pathwyas	Implementaton Framework	Probability of Success
Regulation	Federal Air Regulations	• Strengthen existing standards for hazardous air pollutants emitted by cement plants under NESHAP (Clean Air Act § 112) and/or NSPS (Clean Air Act § 111) • Promulgate standards for CO_2 from new cement plants under NSPS and/or existing cement plants under Clean Air Act § 111(d)	• Strengthening existing standards: Alternative fuels, alternative feedstocks and production processes, decarbonized electricity, efficiency upgrades, CCUS • Promulgating standard for CO_2: All Pathways	• Federal implementation; EPA could act under existing Clean Air Act authority; would require climate-motivated presidential administration • Policy implementation cost would be relatively low since the private sector would lead the effort	• **Scale of impact:** Medium to high • **Timeline:** Medium-term adoption; medium- to long-term impact • **Stakeholder Position:** Public generally supports cleaner air; would face opposition from industry • **Risks:** Vulnerable to challenge in courts or reversal by future government administration • **Alignment:** Complementary to other policies • **Economic Co-benefits:** Improved public health and productivity
Regulation	Performance-based standards	Accelerate adoption of performance-based standards for cement rather than prescriptive standards, e.g., ASTM C1157.	Alternative feedstocks, alternative production processes, clinker substitution, alternative binder chemistries, bio-cement, recarbonation	• State transportation departments and U.S. DOT could adjust their standards for construction materials; depending on the state, this may require enabling legislation • Industry associations (e.g., ASTM and AASHTO) can update their standards to better incorporate alternative cement chemistries • Moderate cost for equipment, practitioner training, and testing	• **Scale of impact:** Large • **Timeline:** Near-term adoption of existing standards; medium- to long-term timeline to update industry association standards; impact begins as soon as standards are adopted • **Stakeholder Position:** Industry opposition • **Risks:** Workforce training, testing and validation, safety • **Alignment:** Foundational to other policies because it enables use of low-carbon cement in a wider variety of contexts

SECTION 1

Introduction

No material on earth is manufactured in greater quantity than concrete.[1] The modern human way of life is literally built on concrete, in large part due to its favorable properties—compressive strength, durability, nonflammability, and resistance to natural forces—and the widespread availability of its constituent ingredients.[2] Cement acts as the binder in concrete and is therefore an essential input to nearly all infrastructure construction, including buildings, roads, and bridges. Production of cement in the United States employs approximately 14,000 workers[3] and outputs 91 million metric tons of cement annually[4] from 92 active cement manufacturing plants across the country.[5]

Concrete, however, comes with a high environmental cost, due in large measure to the greenhouse gas (GHG) emissions and local air pollutants resulting from cement production. U.S. cement production generates about 71.3 million metric tons of carbon dioxide equivalent (MMT CO_2eq) annually, which is equivalent to 4.4 percent of U.S. industrial sector GHG emissions[6] and 1.1 percent of total gross U.S. GHG emissions.[7]

This whitepaper first describes the state of the cement sector in the United States, including context on production technologies, emissions, the structure of the market, and expected future demand. It then provides an overview of the leading technological pathways towards full abatement of cement sector emissions. In the section that follows, we first describe the existing tapestry of enacted and proposed policies, incentives, programs, and regulations to support the adoption of decarbonized cement; we include a matrix summarizing key factors from this survey, including policy design approaches, target technology pathways, appropriate implementation frameworks, and probability of success. Next, the whitepaper identifies policy gaps and barriers that impede the adoption of decarbonized cement. Finally, we propose a series of policy recommendations focused on overcoming the barriers and driving sector-wide decarbonization.

1 Global Cement and Concrete Association. 2021. “Concrete – the world’s most widely used material – targets carbon neutral future.” Available at: https://gccassociation.org/news/concrete-the-worlds-most-widely-used-material-targets-carbon-neutral-future/.

2 International Energy Agency, World Business Council on Sustainable Development, and Cement Sustainability Initiative. 2018. “Technology Roadmap – Low-Carbon Transition in the Cement Industry” Available at: https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry.

3 U.S. Census Bureau. 2024. “County Business Patterns: 2022.” Available at: https://www.census.gov/data/datasets/2022/econ/cbp/2022-cbp.html.

4 U.S. Geological Survey (USGS). 2024. “Cement 2022 tables-only release.” *Minerals Yearbook 2022*, v. I, Metals and Minerals. Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information.

5 Synapse Energy Economics. 2023. *Coming Clean on Industrial Emissions: Challenges, Inequities, and Opportunities in U.S. Steel, Aluminum, Cement, and Coke*. Prepared for Sierra Club. Available at: https://www.sierraclub.org/articles/2023/09/overview-coming-clean-industrial-emissions-report.

6 Id at 30.

7 U.S. EPA. 2024. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022*. Available at: https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-main-text_04-18-2024.pdf.

SECTION 2

Cement Sector Overview

In this section, we discuss current cement production technologies and sources of GHG emissions in detail. We also summarize the current emissions intensity of U.S. cement production and variation between existing manufacturing facilities, discuss cement market structure, and present a projection of U.S. demand for cement through 2050.

2.1 Current Production Technologies

The cement manufacturing process, shown in **Figure 1**, begins with calcareous (calcium-carbonate-rich) raw materials such as limestone and chalk, which cement producers obtain from an open-faced quarry. The material inputs for cement are heavy, and while the manufacturing process sheds approximately one-third of the raw material mass as carbon dioxide (CO_2), cement plants are generally located near quarries to minimize transport costs. High freight costs for finished cement also mean that most U.S. plants serve local customers, causing regional fragmentation in cement markets.[8] Gaps in regional supply are filled with imports from global trade partners, which amount to approximately 22 percent of U.S. cement consumption in 2022.[9]

The first stage in production at a cement facility involves crushing, grinding, and blending raw materials with additives onsite to produce kiln feed. Depending on the type of equipment installed, the plant either removes moisture to create a dry raw mix (dry processing) or adds moisture to create a slurry (wet processing). Equipment in this production stage operates on electricity, producing no direct, additional GHG emissions. The next stage is pyroprocessing, which uses heat to chemically transform the kiln feed into clinker. Clinker is composed of spherical nodules with the chemical properties of cement. To produce clinker, the plant heats the kiln feed in a rotary kiln, which moves kiln feed from one end to the other by rotating. As the kiln feed moves through the rotary kiln, the temperature rises, eventually reaching 1510°C (2750°F). There are five processes that plants may use to produce clinker: dry, wet, semidry, dry with preheater, and dry with preheater/precalciner. The processes result in the same series of chemical reactions but vary in equipment setup and energy efficiency. The most efficient dry process kilns consume 2.8 to 3.2 MMBtu of fuel per metric ton of clinker produced, compared to 5.0 to 6.7 MMBtu per metric ton for typical wet kilns.[10] Of the 94 cement plants included in the most recent U.S. Geological Survey (USGS) dataset, 87 plants use one of the variations of the dry process, while the remaining 7 plants use the wet process.[11] The 87 dry-process plants accounted for 98 percent of U.S. cement production in 2022.[12]

8 U.S. DOE. 2023. "Pathways to Commercial Liftoff: Low-Carbon Cement" Available at: https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf.

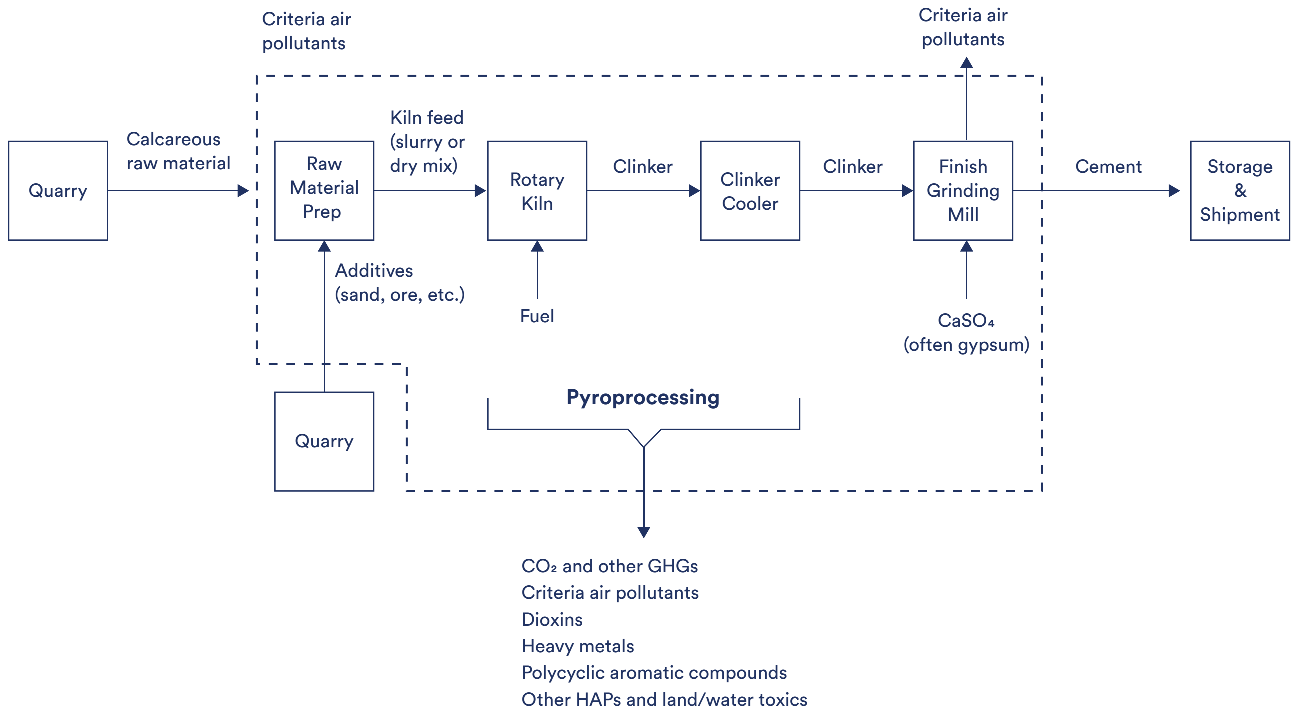
9 USGS. 2024. "Cement 2022 tables-only release." Minerals Yearbook 2022, v. I, Metals and Minerals. Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information.

10 International Energy Agency, 2018. Low-Carbon Transition in the Cement Industry. Available at: https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry.

11 USGS. 2024. "Cement 2022 tables-only release." Minerals Yearbook 2022, v. I, Metals and Minerals. Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information.

12 Ibid.

Figure 1: Cement production process diagram



Notes: The dotted line shows the boundary of the facilities that we categorize as Scope 1 in this report.

The source of heat for kilns also varies, as we discuss in more detail below. The most common kiln fuels are coal, natural gas, coke derived from petroleum refining, and waste (**Table 1**). According to the U.S. Environmental Protection Agency (EPA), the high temperature at which cement kilns operate also makes them an efficient technology for combusting hazardous waste as fuel.[13]

From the kiln, clinker is sent to a cooler and subsequently to a finish grinding mill, which blends the clinker with calcium sulfate (to control setting time) and other additives that affect the material properties of the cement. The finished product, cement, is then ready for shipping.

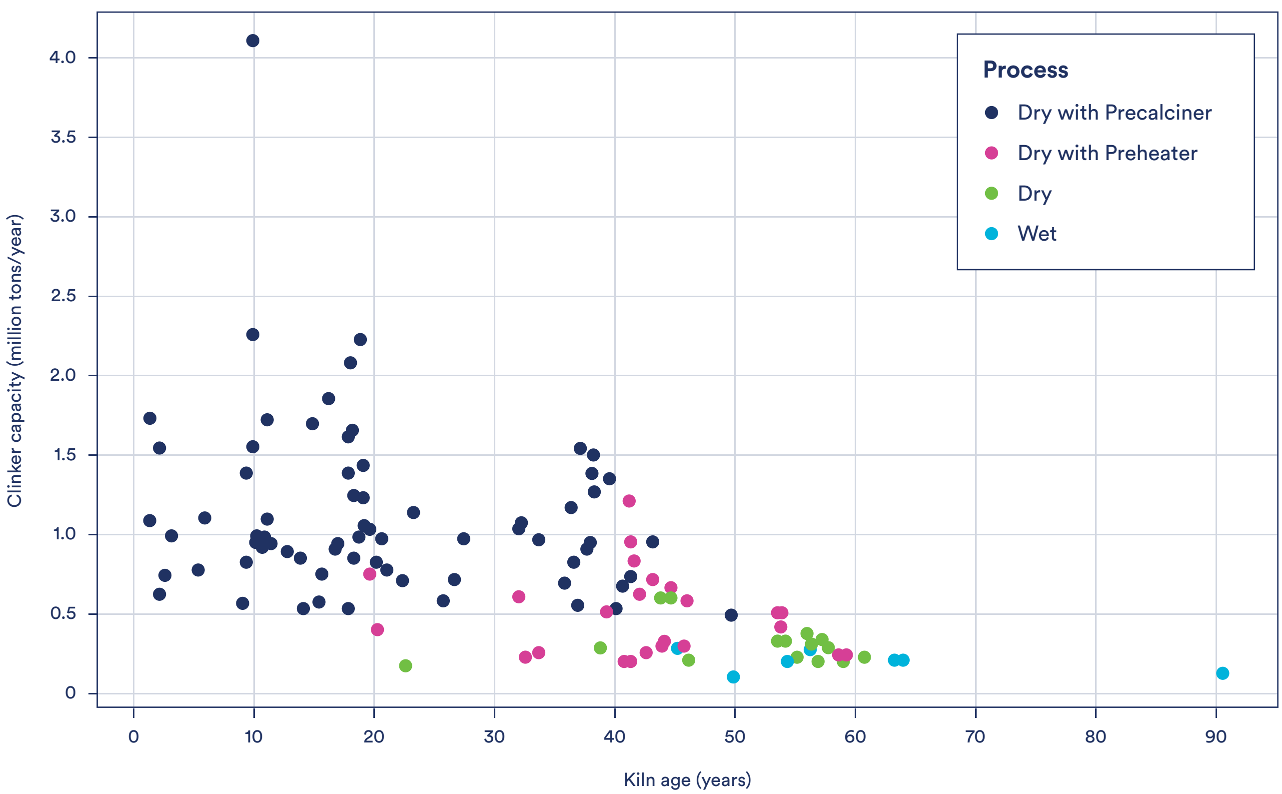
[13] U.S. EPA. 2023. "Cement Kilns Burning Hazardous Waste as Supplemental Fuel." Available at: https://ordspub.epa.gov/ords/guideme_ext/f?p=guideme:gd:::::gd:dioxin_4_5_3.

Recent trends in cement production technologies

The industry has been transitioning away from the wet process towards the more efficient dry process in recent decades. USGS data shows there were 32 cement plants using the wet process in 2000, compared to only seven in 2022.[14] **Figure 2** shows this transition at the kiln level. The oldest operating kilns use the wet process, followed by kilns using the long dry process. The next generation of kilns use the dry process with a preheater, which heats raw materials using hot exhaust gas before they enter the kiln.[15]

The newest kilns (those installed over the past 20 years) almost exclusively use the dry process with both a precalciner and preheater. Precalciner kilns contain an additional combustion vessel to heat raw materials to a high temperature before they reach the core of the kiln.[16] The average clinker capacity per kiln also increased steadily over the past several decades; kilns that are over 50 years old have an average capacity of only 0.27 million tons of clinker per year, compared to 1.25 million tons for kilns that that are less than 20 years old.[17]

Figure 2: Summary of U.S. cement kiln capacity, age, and process in 2019



Source: Portland Cement Association. (2021). U.S. Portland Cement Industry: Plant Information Summary. Includes data through December 31, 2019.

[14] USGS. "Cement Statistics and Information." Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information.

[15] U.S. EPA. 2022. 11.6 Portland Cement Manufacturing. AP 42, Fifth Edition, Volume 1, Chapter 11. U.S. Environmental Protection Agency. Available at: https://www.epa.gov/system/files/documents/2022-03/c11s06_final_0.pdf.

[16] *Portland Cement Ass'n* v. EPA, 665 F.3d 177 (D.C. Cir. 2011).

[17] Portland Cement Association. 2021. U.S. Portland Cement Industry: Plant Information Summary. Includes data through December 31, 2019.

The most appropriate decarbonization pathway for each U.S. cement plant depends on a combination of factors, including kiln age and type. Newer kilns, in particular those that use the dry process with preheater and precalciner, are better suited for retrofit technologies such as carbon capture, utilization, and storage (CCUS) (discussed in more detail below) to reduce their GHG emissions. CCUS is suitable as a retrofit because its installation requires minimal kiln downtime; the CCUS equipment can be constructed alongside operating kilns and brought online while the kiln is briefly offline for its annual relining.[18] Older cement kilns that use less efficient production processes are likely to be approaching the end of their useful lives. Investing in capital-intensive pollution control retrofits for these kilns is likely not feasible, because they may not operate for long enough to recover the cost of the investment. Instead, these older kilns should be replaced at end-of-life with kilns that use newer low- or zero-carbon production methods, discussed in **Section 3** below.

Given that on average about one cement wet-process plant either converts to the dry process or closes per year, the move away from wet processes presents a time-sensitive decarbonization opportunity to ensure that the remaining seven wet-process plants reduce their carbon emissions rather than convert to modernized but conventional production technologies. Once constructed, conventional production facilities have long asset lives of 30 to 50 years, and retiring them early is costly.[19] This urgency for policy to direct investment toward decarbonized cement is underscored by the mean kiln age in the United States—36 years in 2019[20]—which suggests the period from today to 2040 will see substantial equipment turnover and capital investment. The past two decades have also seen continued fuel-switching from coal to natural gas (see **Table 1** below). The share of final energy consumption from coal decreased from 57 percent in 2000 to 31 percent in 2022, while the share of final energy from natural gas increased from only 3.3 percent in 2000 to 24 percent in 2022. The overall energy efficiency of cement production also improved over this time period, with total final energy use decreasing by 14.5 percent, while tons of clinker production changed by less than 1 percent.[21] Looking forward, the remaining efficiency gains available to the industry are likely to be relatively limited, as kilns with outdated technology—wet kilns and dry kilns with neither preheater nor precalciner—represent only 7.3 percent of the 2019 kiln capacity in the United States;[22] see additional discussion in **Section 3.1**.

While final energy consumption in the cement sector has partially shifted from coal to gas, many of the most recently constructed kilns still use coal or coke as their primary fuel (**Figure 3**). Of the 42 kilns constructed between 2000 and 2019, 25 use coal or coke as a primary fuel, compared to only seven that use gas, one that uses alternative fuels, and nine that use multiple fuels.[23] On a national scale, coal costs less than gas on a dollars per MMBtu basis in the industrial sector.[24] This suggests that the economic incentives for fuel-switching from coal to gas at cement kilns depend on the characteristics of local fuel markets and infrastructure availability (e.g., of gas pipelines), rather than a universal advantage of one fuel over the other.

Cement kilns that burn coal or coke are priority candidates for GHG emission control technologies such as CCUS, both because these plants are currently high emitters (making CCUS particularly impactful) and because CCUS generally has a lower cost per ton of carbon captured at facilities with higher concentrations of CO_2 in their exhaust streams[25] (potentially making

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18 U.S. DOE. 2023. "Pathways to Commercial Liftoff: Low-Carbon Cement" Available at: https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf.

18 U.S. DOE. 2023. "Pathways to Commercial Liftoff: Low-Carbon Cement" Available at: https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf.

20 Id.

21 U.S. Geological Survey (USGS). 2024. "Cement 2022 tables-only release." Minerals Yearbook 2022, v. I, Metals and Minerals. Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information; USGS. "Cement Minerals Yearbook 2000." Available at https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/mineral-pubs/cement/170400.pdf.

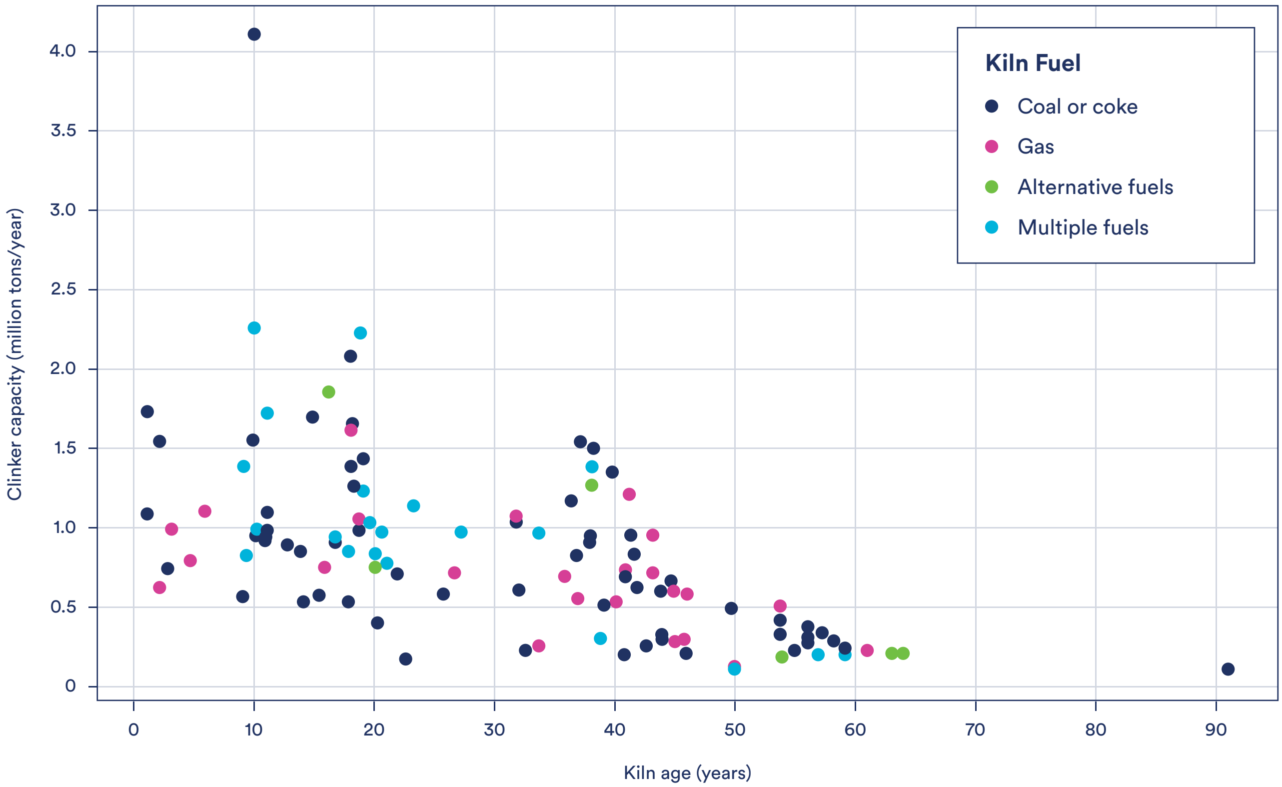
22 Portland Cement Association. 2021. U.S. Portland Cement Industry: Plant Information Summary. Includes data through December 31, 2019.

23 Id.

24 U.S. Energy Information Administration. 2023. State Energy Data System (SEDS) Table ET5. Industrial sector energy price and expenditure estimates, 1970-2022, United States. Available at: https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_prices/ind/pr_ind_US.html&sid=US.

25 Congressional Budget Office. 2023. *Carbon Capture and Storage in the United States.* Available at: https://www.cbo.gov/publication/59832.

Figure 3: Summary of U.S. cement kiln capacity, age, and fuel in 2019



Source: Portland Cement Association. (2021). U.S. Portland Cement Industry: Plant Information Summary. Includes data through December 31, 2019.

CCUS more economic). However, adoption policies must be carefully targeted towards retrofitting existing coal-burning kilns only and should not incentivize additional investment in coal-burning assets, given that coal combustion produces comparatively high emissions of GHGs and toxic and hazardous air pollutants,[26] while lower-emitting fuels and technologies are available.

26 U.S. EPA. 2025. "AP-42: Compilation of Air Emissions Factors from Stationary Sources." Accessed February 3, 2025. Available at: https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors-stationary-sources.

2.2 Sources of Greenhouse Gas Emissions from Cement Production

In 2022, stationary fuel combustion in the U.S. industrial sector generated 1,248 MMT CO_2eq,[27] and industrial processes and product use generated an additional 383 MMT CO_2e nationally.[28] In total, the industrial sector accounted for 26 percent of total gross U.S. emissions (1,631 MMT CO_2eq).[29] Cement production alone accounts for about 71.3 MMT CO_2eq, which is equivalent to 4.4 percent of industrial sector emissions.[30]

One common framework for understanding facility-level GHG emissions is to break emissions down into three scopes. Scope 1 emissions are direct, on-site emissions produced at a facility. Scope 2 emissions are emissions associated with the purchased electricity that a facility consumes. Finally, Scope 3 emissions are associated with the upstream and downstream value chain of the facility. The emissions totals above include Scope 1 and 2 but not Scope 3. In the sections that follow, we discuss sources of each type of emissions at cement production facilities.

Scope 1 emissions

In 2023, Scope 1 emissions from U.S. cement production totaled 65.6 MMT CO_2eq.[31] These emissions fall into two categories: process emissions and fuel combustion emissions. Nearly 60 percent of the GHG emissions from cement-making are non-energy-related and result from the calcining process (thermal decomposition of $CaCO_3$ to CaO and CO_2) that takes place during pyroprocessing.[32] Importantly, because these process

Table 1: Fuel consumption by U.S. cement plants in 2000 and 2022

Category	Fuel	Energy Consumption (TBtu)		Share of Total Energy Consumption(%)	
Scope 1: Conventional fuels	Coal Petcoke Oil Natural gas	214.7 49.0 4.57 12.3	100.6 50.8 1.25 77.5	57.4% 13.1% 1.2% 3.3%	31.5% 15.9% 0.4% 24.2%
Scope 1: Waste fuels	Tires Solid waste Liquid waste	11.2 11.6 29.5	12.3 12.8 24.5	3.0% 3.1% 7.9%	3.8% 4.0% 7.7%
Scope 2	Purchased electricity	41.0	39.9	11.0%	12.5%
Total	**All**	**373.9**	**319.8**	**100%**	**100%**

Source: USGS. (2024). "Cement 2022 tables-only release." Minerals Yearbook 2022, v. I, Metals and Minerals. Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information; USGS. "Cement Minerals Yearbook 2000." Available at https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/mineral-pubs/cement/170400.pdf.

27 U.S. EPA. 2024. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022.* Available at: https://www.epa.gov/system/files/documents/2024-04/us-ghg-inventory-2024-main-text_04-18-2024.pdf. This total includes both heat and electricity generation attributable to the industrial sector.

28 Id.

29 Id.

30 Synapse Energy Economics. 2023. *Coming Clean on Industrial Emissions: Challenges, Inequities, and Opportunities in U.S. Steel, Aluminum, Cement, and Coke. Prepared for Sierra Club.* Available at: https://www.sierraclub.org/articles/2023/09/overview-coming-clean-industrial-emissions-report. Page 30. This total includes both Scope 1 and Scope 2 emissions.

31 U.S. EPA. 2024. "Greenhouse Gas Reporting Program (GHGRP)." Accessed November 2, 2024. Available at: https://www.epa.gov/ghgreporting.

32 U.S. DOE. 2022. *Industrial Decarbonization Roadmap.* DOE/EE-2635. Available at: https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

emissions result from chemical reactions involved in cement production rather than fuel combustion, they cannot be abated through fuel-switching.

The remaining 40 percent of Scope 1 emissions are a result of fuel use. **Table 1** shows the breakdown of final energy use by cement manufacturing in 2000 and 2022, including Scope 1 fuel use and Scope 2 purchased electricity (discussed below). The quantity of coal consumed for cement production has declined by over half since 2000, but coal still accounted for 31 percent of final energy use in 2022. Natural gas consumption has increased by more than a factor of six since 2000 and accounted for 24 percent of energy use in 2022. Use of petcoke remained relatively steady over this time period and accounted for 16 percent of energy use in 2022. Waste fuels—including tires, solid waste, and liquid waste—accounted for an additional 16 percent of energy use in 2022.

Scope 2 emissions

In 2020, Scope 2 emissions from cement production were much lower than Scope 1 emissions at 4.4 MMT CO_2eq.[33] While nearly all Scope 1 emissions are emitted during pyroprocessing (in particular from the kiln and preheater/precalciner), the majority of Scope 2 emissions are related to stages of cement production immediately before and after pyroprocessing (e.g., crushing and milling), where facilities use electricity to power equipment such as motors and lighting.[34]

Scope 3 emissions

Scope 3 emissions are the broadest group of GHG emissions, encompassing indirect emissions from both upstream and downstream processes. EPA categorizes Scope 3 emissions into 15 distinct categories and includes the GHG emissions from the assets not owned or controlled by the reporting organization.[35]

A 2022 survey of 28 cement companies by CDP (formerly the Carbon Disclosure Project) found that Scope 3 emissions accounted for 16 percent of the participating companies' total GHG emissions, with 80 percent falling under Scope 1 emissions and 4 percent under Scope 2 emissions. **Table 2** shows the survey results broken down by the EPA's Scope 3 GHG emission categories.[36,37]

The dominant Scope 3 categories are defined as follows:

- **Category 1** includes all upstream emissions from the production of products and services purchased by the company, other than fuels and electricity. This may include raw materials, equipment, and subcontractors' services. Emissions can be estimated using supplier-specific data or methods that rely on industry average data, such as "spend-based," "average-based," or a hybrid of the two. The emissions calculated for Category 1 are "cradle-to-grave" emissions and should include the fuel and electricity to produce, transport (in the companies' own vehicles), use, and dispose of the purchased goods and services.
- **Category 3** covers the cradle-to-grave emissions from upstream extraction, production, and transportation of any fuel or electricity purchased by the company. For example, this may include the energy needed to mine, refine, and transport the coal used at a cement factory for powering the manufacturing process, as well as any upstream natural gas emissions.
- **Category 4** includes emissions from upstream transportation and distribution of products purchased by the company but moved and stored in vehicles and facilities owned externally. This could include shipping of goods by rail, air, or ship and the storage of goods in a warehouse by a supplier.
- **Category 9** contains the downstream transportation and distribution emissions from transporting sold products via vehicles and storage in facilities not owned by the reporting company.

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33 Synapse Energy Economics. 2023. *Coming Clean on Industrial Emissions: Challenges, Inequities, and Opportunities in U.S. Steel, Aluminum, Cement, and Coke.* Prepared for Sierra Club. Available at: https://www.sierraclub.org/articles/2023/09/overview-coming-clean-industrial-emissions-report.

34 U.S. Department of Energy. 2023. "Pathways to Commercial Liftoff: Low-Carbon Cement" Available at: https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf. Page 10.

35 U.S. Environmental Protection Agency. 2024. *Scope 3 Inventory Guidance – Description of Scope 3 Emissions.* Available at: https://www.epa.gov/climateleadership/scope-3-inventory-guidance.

36 World Business Council on Sustainable Development (WBCSD). 2016. *Cement Sector Scope 3 GHG Accounting and Reporting Guidance.* Available at: https://www.wbcsd.org/wp-content/uploads/2023/12/Cement-Sector-Scope-3-GHG-Accounting-and-Reporting-Guidance.pdf.

37 CDP. 2022. *CDP Technical Note: Relevance of Scope 3 Categories by Sector: CDP Corporate Questionnaire.* Updated June 2024. Available at: https://cdn.cdp.net/cdp-production/cms/guidance_docs/pdfs/000/003/504/original/CDP-technical-note-scope-3-relevance-by-sector.pdf.

Table 2: Largest contributing emissions categories to Scope 3 emissions

Scope 3 Emissions Category	Description	% of Scope 3 Emissions
1	Purchased fuel and goods	39%
3	Fuel- and energy-related	21%
4	Upstream distribution and transportation	21%
9	Downstream distribution and transportation	16%
10-15	Other downstream	2%
2, 5-8	Other upstream	1%

Source: World Business Council on Sustainable Development. (2016). Cement Sector Scope 3 GHG Accounting and Reporting Guidance; CDP (2022) CDP Technical Note: Relevance of Scope 3 Categories by Sector: CDP Corporate Questionnaire.

Of the three emission types, Scope 3 emissions are usually the hardest to quantify. The EPA offers two sources for emission factors for Scope 3 emission estimates—the U.S. Environmentally-Extended Input-Output models (GHG emissions per dollar spending) and the Greenhouse Gas Emission Factors Hub.[38] Notably, Scope 3 emissions can vary between blending, grinding, and vertically integrated cement plants.[39]

2.3 Greenhouse Gas EmissionsIntensity of U.S. Cement

As of 2020, the capacity-weighted average GHG emissions intensity of U.S. cement was 0.83 tons of CO_2e per ton of cement excluding Scope 3 emissions (**Figure 4**). Scope 1 accounted for 94 percent of these emissions (0.78 tons of CO_2e per ton of cement) and Scope 2 accounted for the remaining 6 percent (0.05 tons of CO_2e per ton of cement).[40]

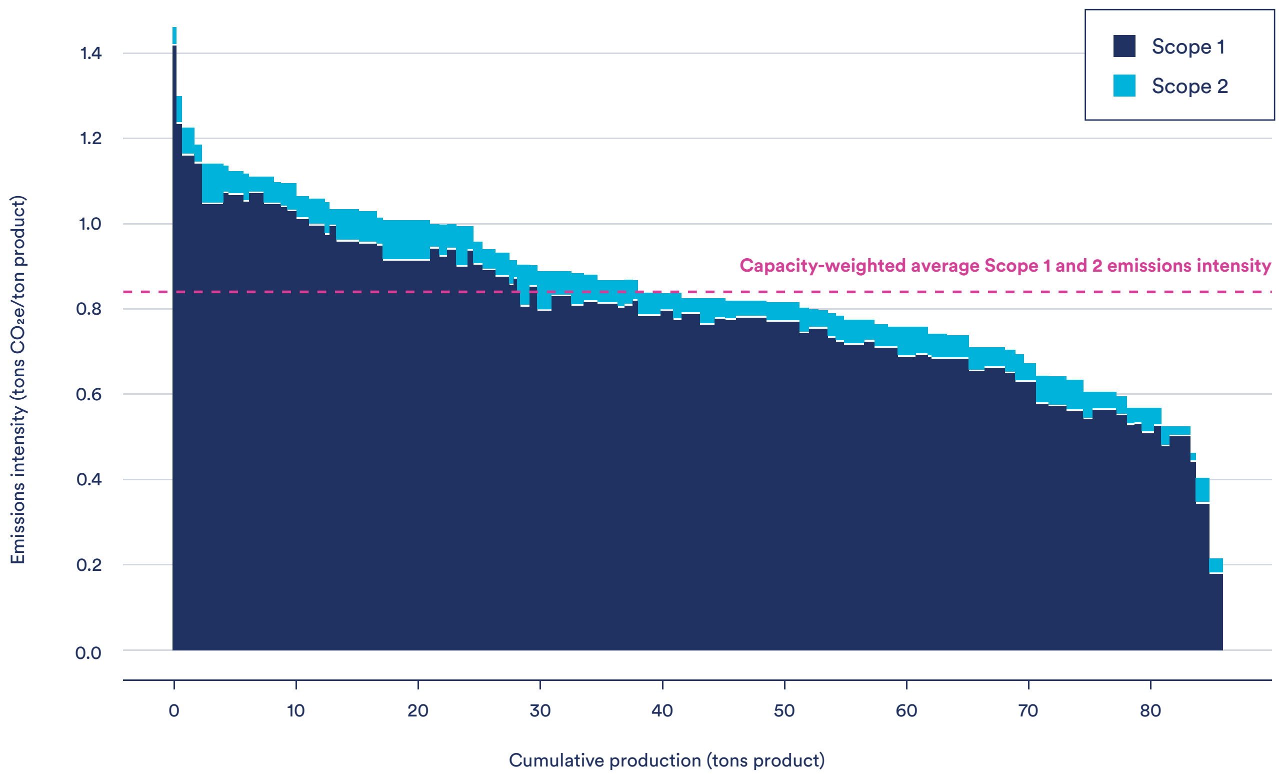
The average emissions intensity of cement production varies by census region (**Table 3**). The 25 percent of cement produced in the Midwest has the highest average emissions intensity at 0.97 tons of CO_2e per ton of cement. Cement plants in the South and West have average emissions intensities of 0.81 and 0.80 tons of CO_2e per ton of cement, respectively, while the 8 percent of cement produced in the Northeast has a lower emissions intensity of 0.62 tons of CO_2e per ton of cement. **Figure 5** shows this distribution of emissions intensity in map form—each circle shows the location of a cement plant, and the color indicates the emissions intensity of cement produced at that facility.

38 U.S. Environmental Protection Agency. 2024. *Scope 3 Inventory Guidance – Description of Scope 3 Emissions*. Available at: https://www.epa.gov/climateleadership/scope-3-inventory-guidance.

39 World Business Council on Sustainable Development (WBCSD). 2016. *Cement Sector Scope 3 GHG Accounting and Reporting Guidance.* Available at: https://www.wbcsd.org/wp-content/uploads/2023/12/Cement-Sector-Scope-3-GHG-Accounting-and-Reporting-Guidance.pdf.

40 Synapse Energy Economics. 2023. *Coming Clean on Industrial Emissions: Challenges, Inequities, and Opportunities in U.S. Steel, Aluminum, Cement, and Coke.* Prepared for Sierra Club. Available at: https://www.sierraclub.org/articles/2023/09/overview-coming-clean-industrial-emissions-report. Page 49.

Figure 4: Emissions curve for U.S. cement plants, 2022



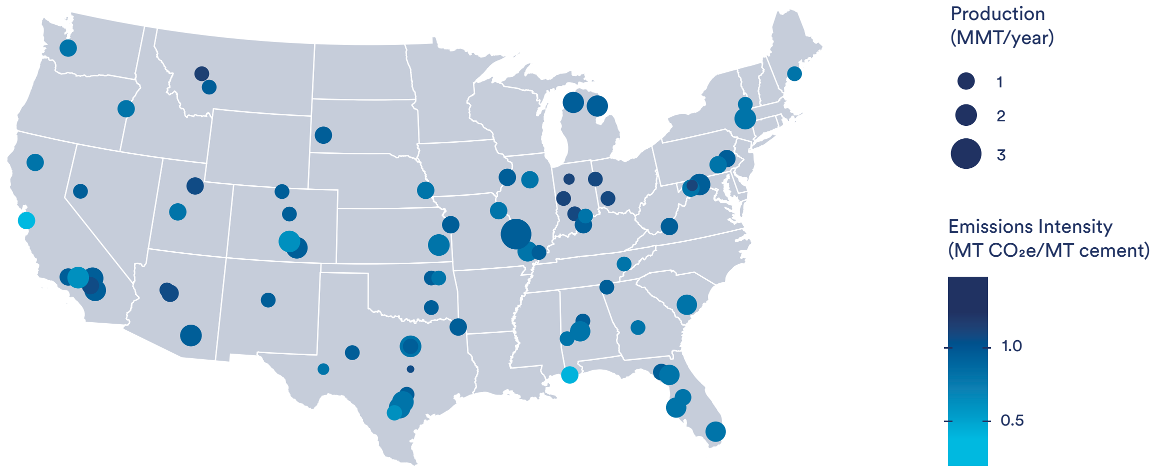
Source: Synapse Energy Economics. (2023). "Coming Clean on Industrial Emissions: Final Database 2023-06." Prepared for Sierra Club. Available at: https://www.sierraclub.org/articles/2023/09/overview-coming-clean-industrial-emissions-report.

Table 3: Emissions intensity of U.S. cement production by census region

Census Region	Count of Plants	Share of National Cement Production	Cement Emissions Intensity ($MT\ CO_2e/MT$ of product)
Midwest	21	25%	0.97
South	36	42%	0.81
West	23	24%	0.80
Northeast	10	8.4%	0.62
Total	**90**	**100%**	**0.83**

Source: Synapse Energy Economics. 2023. "Coming Clean on Industrial Emissions: Final Database 2023-06." Prepared for Sierra Club. Available at: https://www.sierraclub.org/articles/2023/09/overview-coming-clean-industrial-emissions-report. Two plants are omitted from the analysis due to missing data.

Figure 5. Map of facility-level production capacity (point size) and Scopes 1 and 2 emissions intensity (color)

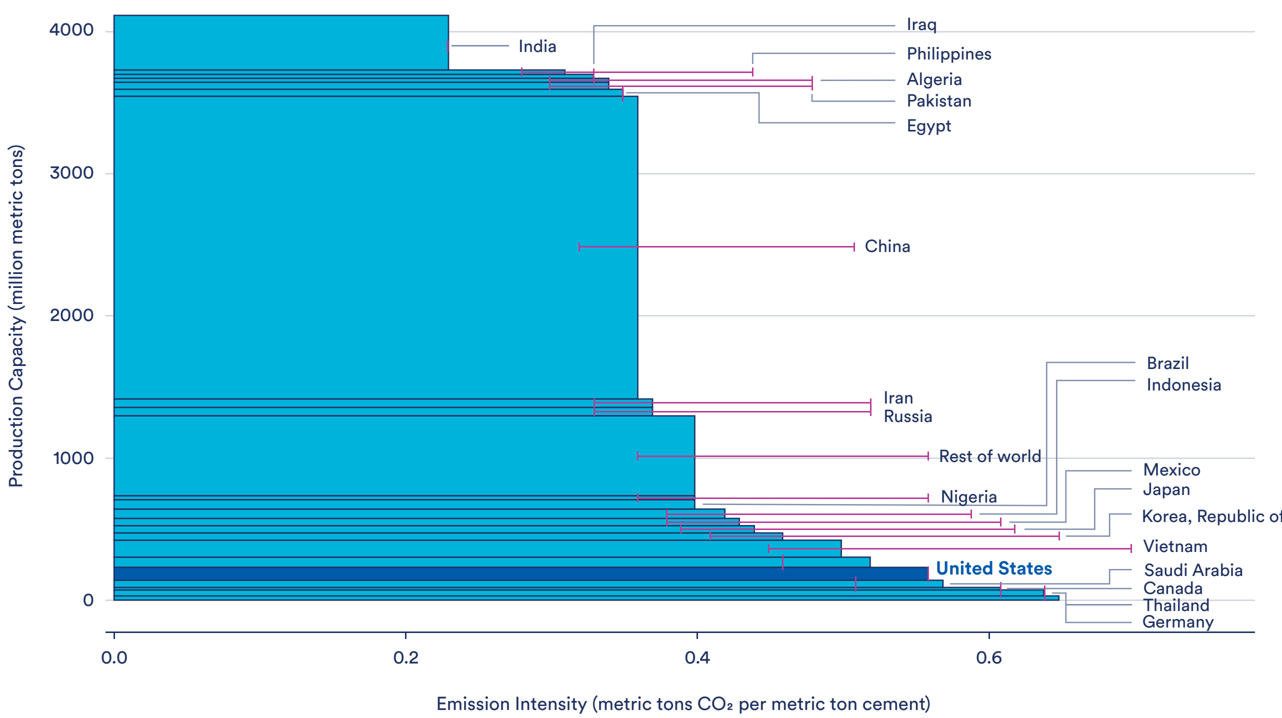


Source: Synapse Energy Economics. (2023). "Coming Clean on Industrial Emissions: Final Database 2023-06." Prepared for Sierra Club. Available at: https://www.sierraclub.org/articles/2023/09/overview-coming-clean-industrial-emissions-report. Darker blue indicates higher emissions intensity. Larger point size indicates higher production capacity.

Carbon intensity of U.S. cement relative to other countries

Compared to most other major cement producing countries, the United States produces cement at a higher emissions rate. The United States is a more carbon-intensive producer than many of our largest cement trading partners, such as Canada and Mexico (**Figure 6**). The global average emission intensity for cement is approximately 0.630 tons of CO_2 per ton of cement, with U.S. production around 20 percent higher than other major cement-producing nations.[41,42]

Figure 6: Comparison of U.S. cement emission intensity to global supply



Source: Synapse analysis of data from USGS, Global Carbon Budget, and GCCA. Excludes emissions from onsite power generation. Error bars indicate 95 percent confidence interval for countries that do not appear in the GCCA dataset. Note, GCCA and Global Carbon Budget emission accounting protocols differ from U.S. EPA data used elsewhere in this report, which may cause appearance of inconsistent results.

USGS. (2024). Cement Statistics and Information. Mineral yearbook 2022. Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information.

Our World in Data and Global Carbon Budget. (2024). Accessed October 16, 2024. Available at: https://ourworldindata.org/grapher/annual-co2-cement.

Global Cement and Concrete Association. (2024). "GNR 2.0 – GCCA in Numbers." Accessed December 19, 2024. Available by request at: https://gccassociation.org/sustainability-innovation/gnr-gcca-in-numbers/.

41 World Resources Institute, "The US Needs to Lower Cement Emissions – 'Blended Cement' can help," May 9, 2024.

42 Note, GCCA and Global Carbon Budget emission accounting protocols differ from U.S. EPA data used elsewhere in this report, which may cause appearance of inconsistent results.

2.4 Criteria Air Pollutants, Hazardous Air Pollutants, and Human Health Impacts

In addition to GHGs, cement plants release a range of other pollutants with negative health and environmental impacts. The Clean Air Act requires that companies monitor and report to EPA certain pollutants, including "criteria air pollutants," for which EPA sets National Ambient Air Quality Standards (NAAQS), as well as GHG emissions. Criteria air pollutants include ground-level ozone, particulate matter, carbon monoxide, lead, sulfur dioxide, and nitrogen dioxide.[43] The Clean Air Act also requires EPA to monitor and report certain listed "hazardous air pollutants"—highly toxic pollutants that are known to cause cancer and other serious health impacts for which EPA sets Maximum Achievable Control Technology-based Standards (MACT).[44] Examples of listed hazardous air pollutants include polycyclic aromatic compounds, dioxins, mercury, and other toxic metals found in fine particulates. The Clean Air Act lists almost 200 individual hazardous air pollutants and EPA can make modifications to the list through rulemaking.[45] Various pollution control systems are used to reduce the toxic pollutants from cement plants, including fabric filter baghouses, regenerative thermal oxidizers, selective non-catalytic reduction systems, and slurry scrubbers.[46] In total, cement plants are responsible for releasing 140 different regulated pollutants via air, land, and water (**Table 4**).

EPA's Risk-Screening Environmental Indicators (RSEI) model assesses the relative risk posed by individual cement plants (among other facilities) and the toxic chemical releases into the environment (air and water).[47] RSEI evaluates risk from individual facilities using reported quantities of chemical releases, the fate and transport of the chemicals through the environment, the size and location of the exposed human population, and the chemicals' toxicity levels. The cement manufacturing industry has the 83rd highest impact risk out of 531 industries in the United States—posing comparable risk to several other manufacturing industries, such as paper mills and primary aluminum production.

Table 4: Summary of chemical releases in the cement industry by exposure pathway, 2020

Exposure Pathway	Number of Distinct Chemicals
Land	26
Water	17
Air	139
Total	**140**

Note: The total number of pollutants reported is not equal to the sum of the number of chemicals reported by each medium of release because individual chemicals can be released across multiple media. Sources: U.S. EPA. (2021). Toxic Releases Inventory (2020).

U.S. EPA. (2021). National Emissions Inventory (2020).

43 U.S. EPA. 2022. "Criteria Air Pollutants." Available at: https://www.epa.gov/criteria-air-pollutants. See also 42 U.S.C. § 7409.

44 U.S. EPA. 2022. "What are Hazardous Air Pollutants?" Available at: https://www.epa.gov/haps/what-are-hazardous-air-pollutants.

45 U.S. EPA. 2022. "Initial List of Hazardous Air Pollutants with Modifications." Available at: https://www.epa.gov/haps/initial-list-hazardous-air-pollutants-modifications.

46 Based on Synapse review of permit data from the U.S. EPA's RACT/BACT/LAER Clearinghouse, available at: https://www.epa.gov/catc/ractbactlaer-clearinghouse-rblc-basic-information.

47 U.S. EPA. 2024. "Risk-Screening Environmental Indicators (RSEI) Model." Accessed November 1, 2024. Available at: https://www.epa.gov/rsei. This model is based on EPA's Toxic Release Inventory, and does not include public health risk related to criteria pollution releases, although metal toxics and other toxics can be associated with criteria pollution releases, specifically particulate matter and SO_2.

Prior analysis using EPA's CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA) indicates that eliminating particulate matter emissions[48] from cement production would prevent 179 to 405 premature deaths annually in the United States, among other adverse health impacts (**Table 5**).

Industrial facilities in the United States frequently contribute to environmental, socioeconomic, and health inequities because they are concentrated in urban areas with disadvantaged communities and disproportionately high pollution levels from industry, heavy transport, and on-site combustion of fossil fuels.[49] Siting facilities in low-income and racial minority communities occurs with

Table 5. Reductions in adverse health impacts due to eliminating fine particulate matter pollution from cement plants

Health Endpoint	Change in Incidence (cases, annual)
Mortality	**Low** 179 **High** 405
Nonfatal Heart Attacks	**Low** 19 **High** 181
Infant Mortality	1
Hospital Admits, All Respiratory	45
Hospital Admits, Cardiovascular (except heart attacks)	45
Acute Bronchitis	237
Upper Respiratory Symptoms	4,290
Lower Respiratory Symptoms	3,017
Emergency Room Visits, Asthma	92
Asthma Exacerbation	4,485
Minor Restricted Activity Days	128,610
Work Loss Days	21,761

Source: Eash-Gates, P., O. Griot, A. Hopkins, L. Metz, E. Sinclair, J. Smith. (2023). Coming Clean on Industrial Emissions: Challenges, Inequities, and Opportunities in U.S. Steel, Aluminum, Cement, and Coke. Prepared by Synapse Energy Economics for Sierra Club.

48 This includes PM2.5 and precursors of secondary $PM_{2.5}$, including sulfur dioxide, nitrogen oxides, ammonia, and volatile organic compounds.

49 Bell, Michelle L., & Ebisu, Keita. 2012. "Environmental Inequality in Exposures to Airborne Particulate Matter Components in the United States." Environmental Health Perspectives, 120(12), 1669–1704. Available at: https://ehp.niehs.nih.gov/1205201/.

greater frequency than in white communities, in part due to disregard by policymakers.[50,51] Such inequities occur in some cement manufacturing communities, with the greatest disproportionate impacts occurring in Florida, Alabama, Puerto Rico, Texas, and California; however, on average, the neighborhoods surrounding cement manufacturing facilities are equally or less disadvantaged than the United States population at large.[52] For example, 27 percent of the population in communities surrounding cement facilities are people of color, compared to 40 percent in the United States at large. Similarly, cement communities have higher educational attainment, lower linguistic isolation, lower unemployment rates, and lower environmental indicators for air pollution (fine particulate matter, air toxics respiratory exposure, diesel particulate matter, and more).[53]

2.5 Market Structure

The cement value chain is unusual because it is consolidated at both ends—there are relatively few suppliers and purchasers—but fragmented in the middle, with multiple tiers of small intermediaries including ready-mix and precast concrete companies, wholesale retailers, contractors, and subcontractors (discussed in more detail below).[54]

On the supply side, there are 92 active cement plants in the United States.[55] The top cement-producing states are Texas, California, Missouri, and Florida, which collectively accounted for 43 percent of U.S. cement production in 2022.[56] Ownership of U.S. cement plants is relatively concentrated: 26 parent companies own all U.S. cement plants, of which 10 parent companies own three-quarters of cement plants and 80 percent of cement clinker capacity (**Table 6**). Most of these companies are part of large multinational corporations or are subsidiaries of multinational holding companies. For example, Holcim is headquartered in Switzerland and operates in 70 countries worldwide, and Lehigh Hanson is now part of the Germany-headquartered Heidelberg Materials. Using clinker capacity as a proxy for market share, the industry is not highly concentrated, using the standard Herfindahl–Hirschman Index analysis for market share concentration.[57] This implies that further market concentration in which larger firms purchase smaller firms is possible before market concentration concerns are pertinent. Additionally, the producer side of the market could continue to narrow, with fewer suppliers.

Notably, leading companies, including Holcim and Heidelberg, are pursuing cement CCUS projects in Europe, driven in large measure by the EU Emissions Trading System. Thus, these companies are developing the capabilities for cement decarbonization but are not pursuing such projects to the same extent in the United States due to policy uncertainty, insufficient incentives, or both. Heidelberg Materials' Mitchell Cement Plant Decarbonization Project, a recipient of U.S. DOE Industrial Demonstrations Program funding, is one notable exception.[58]

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50 Mohai, P. and Saha, R., 2015. Which came first, people or pollution? A review of theory and evidence from longitudinal environmental justice studies. Environmental Research Letters, 10(12), p.125011. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/10/11/115008/pdf.

51 Paul, I., Pries, C., and Sarinsky, M. 2021. Improving Environmental Justice Analysis: Executive Order 12,898 and Climate Change. Institute for Policy Integrity. Available at: https://policyintegrity.org/publications/detail/improving-environmental-justice-analysis.

52 Eash-Gates, P., O. Griot, A. Hopkins, L. Metz, E. Sinclair, J. Smith. 2023. *Coming Clean on Industrial Emissions: Challenges, Inequities, and Opportunities in U.S. Steel, Aluminum, Cement, and Coke.* Prepared by Synapse Energy Economics for Sierra Club.

53 Id.

54 U.S. Department of Energy. 2023. "Pathways to Commercial Liftoff: Low-Carbon Cement." Available at: https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf. Page 17.

55 Synapse Energy Economics. 2023. "Coming Clean on Industrial Emissions: Final Database 2023-06." Prepared for Sierra Club. Available at: https://www.sierraclub.org/articles/2023/09/overview-coming-clean-industrial-emissions-report.

56 United States Geological Survey (USGS). 2024. "Cement 2022 tables-only release." Minerals Yearbook 2022, v. I, Metals and Minerals. Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information.

57 The U.S. Department of Justice and Federal Trade Commission use the Hefindahl-Hirschman Index (HHI) in their analysis of market concentration when considering anti-trust enforcement. HHI is calculated by summing the squares of the market share of each firm competing in the market.

58 U.S. DOE. 2025. "Industrial Demonstrations Program Selected and Awarded Projects: Cement and Concrete" Available at: https://www.energy.gov/oced/industrial-demonstrations-program-selected-and-awarded-projects-cement-and-concrete.

Table 6: Major U.S. cement manufacturers

Parent Company	Number of Cement Plants	Percent of U.S. Cement Plants	Percent of U.S. Cement Clinker Capacity
Holcim Participations (US) Inc.	13	14.1%	19.6%
Lehigh Hanson Inc.	12	13.0%	11.4%
Eagle Materials Inc.	7	7.6%	5.7%
RC Lonestar Inc. (Buzzi Unicem USA)	7	7.6%	9.3%
CRH Americas Inc.	8	8.7%	9.2%
Cemex Inc.	7	7.6%	10.3%
GCC Of America Inc.	5	5.4%	3.3%
Argos USA, LLC	4	4.3%	5.4%
Giant Cement Holding Inc.	3	3.3%	2.4%
Taiheiyo Cement USA Inc. (CalPortland Co.)	3	3.3%	4.2%
16 other parent companies	22	23.9%	19.3%
Unavailable	1	1.1%	
Total	**92**	**100%**	**100%**

Source: Synapse Energy Economics. (2023). "Coming Clean on Industrial Emissions: Final Database 2023-06." Prepared for Sierra Club. Available at: https://www.sierraclub.org/articles/2023/09/overview-coming-clean-industrial-emissions-report; Portland Cement Association. (2019). U.S. Portland Cement Industry: Plant Information Summary, Table 9. Plant count for CRH Americas includes one plant that CRH co-owns with two other companies.

On the demand side, government procurement accounts for 46 percent of U.S. cement purchases, with about 25 percent of this cement procured with federal funds, either directly or through state grants.[59] The concrete produced with that cement is used to construct infrastructure such as roads, highways, wastewater infrastructure, and public buildings. The rest of the market is primarily private building construction.[60] Because the public sector—especially federal and state departments of transportation—accounts for such a large share of cement consumption, the cement industry is especially ripe for "buy clean" policies and advance market procurement (commitments to purchase future production), discussed in more detail below. In 2018, 46 percent of domestic cement consumption went to public construction projects.[61] Of these, 69 percent of the cement consumption was used for construction of highways and streets, with the remaining 31 percent going to construction related to sewage and waste disposal, water supply systems, conservation, buildings, and public safety.

59 Hasanbeigi, A., D. Shi, H. Khutal. 2021. "Federal Buy Clean Policy for Construction Materials in the United States." Global Efficiency Intelligence. Available at: https://www.aceee.org/sites/default/files/pdfs/ssi21/panel-4/Shi.pdf.

60 U.S. Department of Energy. 2023. "Pathways to Commercial Liftoff: Low-Carbon Cement." Available at: https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf. Page 17.

61 Hasanbeigi, A., D. Shi, H. Khutal. 2021. "Federal Buy Clean Policy for Construction Materials in the United States." Global Efficiency Intelligence. Available at: https://www.aceee.org/sites/default/files/pdfs/ssi21/panel-4/Shi.pdf.

Between cement production plants and consumers of cement, there are multiple tiers of intermediaries. Approximately three-quarters of shipped cement goes to ready-mix concrete companies and then to contractors and sub-contractors who eventually use it in construction.[62] An additional fifth of cement produced similarly goes to precast companies, wholesalers, and big box retailers who then re-sell it to contractors.[63] Only one-tenth of cement goes from the production plant to the ultimate end use via a single vertically integrated direct contractor.[64] The presence of intermediaries complicates access to finance, because off-takers who might be willing to pay a premium for low-carbon cement do not contract directly with the producers of cement.[65] Because of the cyclical nature of the construction industry, cement purchasers typically buy cement through spot transactions.[66] State and local governments typically issue requests for supplier proposals for cement purchases for particular projects making it difficult to provide assurance about future demand and to secure low-cost financing.[67] For example, project financing is one tool that companies often use to finance capital-intensive infrastructure projects. Under a project finance structure, lenders loan money for a project based solely on the specific project's risk and future cash flows, and they do not have recourse to the company developing the project for repayment of the debt.[68] This allows the company developing the project to record the debt off of its own balance sheet,[69] making it possible to finance large projects that would otherwise be too expensive or risky for the company to undertake. Because project financing relies on long-term off-take agreements to reduce risk for lenders, it is generally unavailable to U.S. cement producers, which must instead finance new cement plants on the balance sheet, either from existing assets and cash flow or by using traditional corporate finance.[70]

Cement plants depend on large production volumes and low-cost fuel and freight costs to maintain their economic competitiveness.[71] Plant downtime is expensive because of the high opportunity cost of foregone production. Cement producers typically take kilns offline every one to two years to reline them, but major overhauls occur on a much longer timescale.[72,73] Interventions that necessitate long plant downtimes or that increase fuel or freight costs will increase the cost of the final product. Cement prices are dictated more by fluctuations in macroeconomic conditions such as increased demand for housing, transportation infrastructure, and other impacts, than by supply pressures.[74] See in **Figure 7**, for example, the rise in national average cement prices during the mid-2000s housing boom and subsequent crash during the Great Recession. In 2020, the industry was affected by dampening demand from the Covid-19 pandemic and then by the subsequent run up in prices in 2021 and 2022 after economic activity increase. National average cement prices are at near all-time high, around $152 per ton, with annualized growth from 2019 to 2024 of 4.8 percent.

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62 U.S. Department of Energy. 2023. "Pathways to Commercial Liftoff: Low-Carbon Cement." Available at: https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf. Page 16.

63 Ibid.

64 Ibid.

65 Id at 47.

66 Ibid.

67 Ibid.

68 Groobey, C, Pierce, J, Faber, M, and Broome, G. Project Finance Primer for Renewable Energy and Clean Tech Projects. Available at: https://www.wsgr.com/PDFSearch/ctp_guide.pdf.

69 Ibid.

70 Ibid.

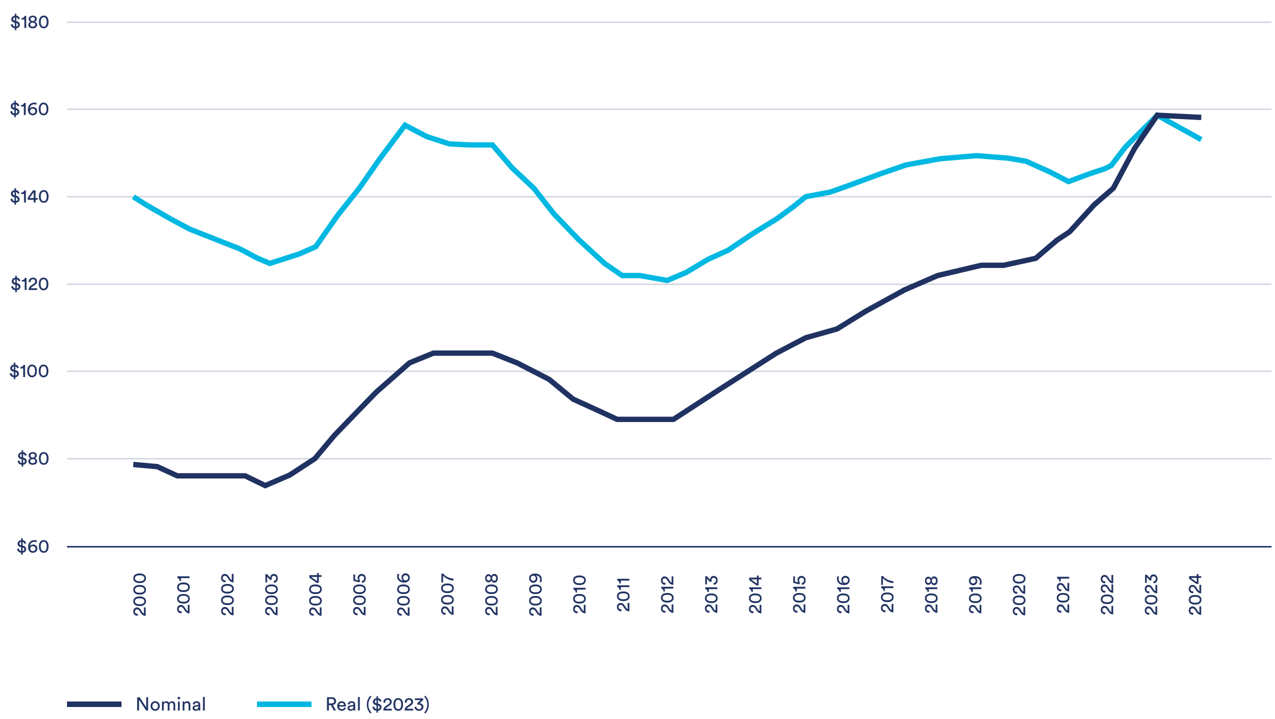
71 Ibid.

72 Ibid.

73 Metso:Outotec. *Rotary Kiln Maintenance*. Accessed 1/2/2025. Available at: https://www.metso.com/globalassets/services/pyro/ebook-kfs-rotary-kiln-maintenance-4136_en_web.pdf.

74 *See* IBISWorld, Business Environment Profiles – United States, Price of Cement. (Aug. 22, 2024). Available at: https://www.ibisworld.com/us/bed/price-of-cement/190/.

Figure 7: National average cement prices (U.S. dollars per ton)



Source: IBISWorld, Business Environment Profiles – United States, Price of Cement. (Aug. 22, 2024). Note: IBISWorld uses data from the US Geological Survey, which tracks a composite cement price that is a volume-weighted average of all Portland cement and masonry cement.

It is worth noting that increases in the per-unit cost of cement increases construction project costs only slightly. For example, the U.S. Department of Energy (DOE) estimates that cement produced using 95 percent carbon capture (discussed in **Section 3.4**) would have a price premium of 20 to 40 percent.[75] This translates to an increase in construction costs of only 0.09 to 0.19 percent on average (more for concrete-intensive projects) since the material cost of cement accounts for only 0.45 percent of typical project costs.[76] To enable the expansion of low-carbon cement production, the creation of market structures that allow interested customers to pay this price premium to cement producers will be key.

75 U.S. Department of Energy. 2023. "Pathways to Commercial Liftoff: Low-Carbon Cement." Available at: https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf.

76 U.S. Bureau of Economic Analysis. 2024. "U.Gross Output by Industry – Detail Level." Accessed November 5, 2024. Available at: https://www.bea.gov/itable/gdp-by-industry.

Imports and exports of cement

Although cement is a heavy material with high freight costs, there is a robust trade in clinker and cement across borders. The U.S. imported approximately 26.5 million metric tons of cement and clinker in 2023, although the Census Bureau notes that this is likely an underestimate given the difficulty of accurately counting overland imported clinker from Canada on an informal entry basis.[77] In total, imports amount to roughly $2.7 billion and more than a quarter of all U.S. cement production. Imports have increased by roughly 68 percent since 2019. **Table 7** lists the United States's top five countries of import. These five countries account for roughly 80 percent of total cement imports by quantity and value into the United States. As of March 2025, the United States does not impose any import tariffs on Portland cement or clinker.[78] Notably, the U.S. cement emission intensity falls within the estimated emission intensity ranges for our trade partners. **Figure 8** shows that U.S. cement production has remained relatively steady over the last decade while consumption has increased from 90 million tons in 2014 to an estimated 117 million tons in 2023, with much of this increase in consumption made up by imports.[79]

The United States is not a major exporter of cement. It exported just 243,200 metric tons in 2023, primarily to Canada (223,000 metric tons) and Mexico (5,500 metric tons).[80] The total value of exported cement is around $45 million, a small amount compared to the domestic size of the cement industry.[81]

Table 7: Top five countries of import of cement (H.S. Code 2523) to United States, 2023

Country of Origin	Quantity (million metric tons)	Value—cost, insurance, freight (2023$ million)	Estimated emission Intensity (ton CO_2 per ton cement)
Turkey	7.9	$730	0.46–0.73
Canada	4.9	$569	0.61
Vietnam	3.9	$356	0.45–0.70
Greece	2.1	$187	0.52–0.82
Mexico	2.0	$254	0.38–0.61

Sources: USGS Mineral industry Surveys, Cement in December 2023, Table 5.

Synapse analysis of data from USGS, Global Carbon Budget, and GCCA. Excludes emissions from onsite power generation. Emission intensity ranges indicate 95 percent confidence interval for countries that do not appear in the GCCA dataset. Note, GCCA and Global Carbon Budget emission accounting protocols differ from U.S. EPA data used elsewhere in this report, which may cause appearance of inconsistent results.

77 USGS, 2024. Mineral Industry Surveys: Cement in December 2023, at 31. Available at: https://www.usgs.gov/centers/national-minerals-information-center/mineral-industry-surveys

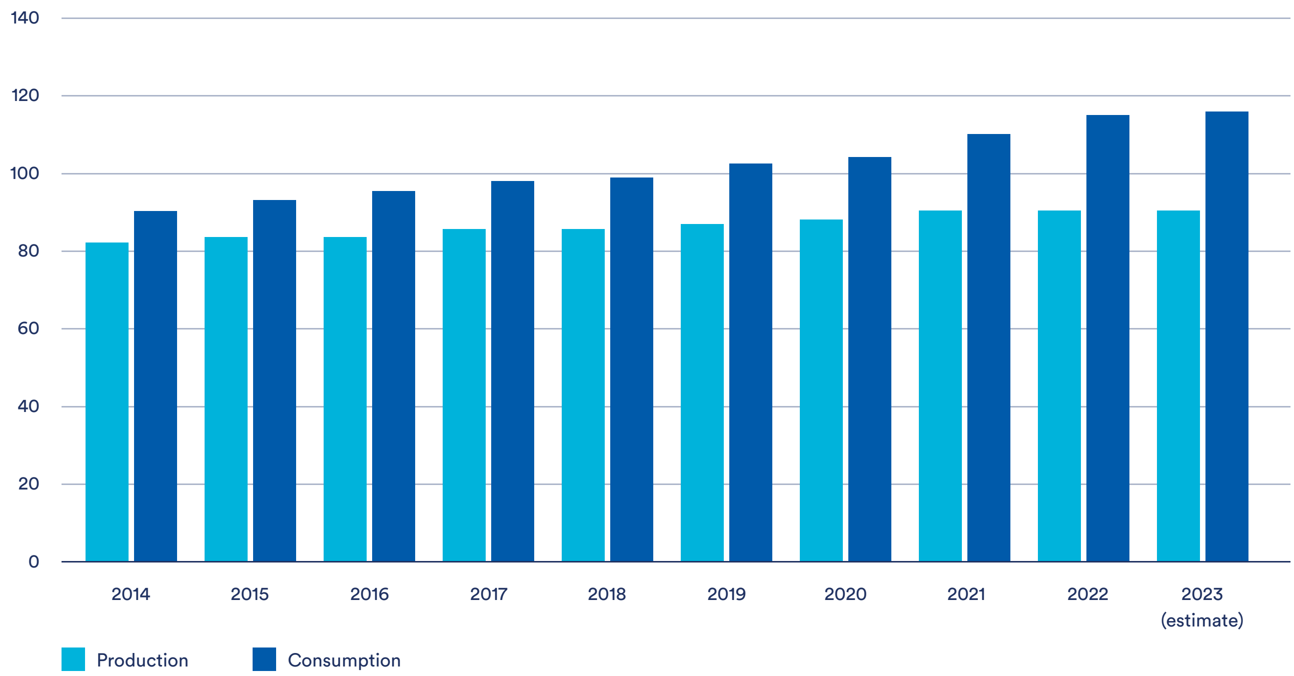
78 U.S. International Trade Commission. Harmonized Tariff Schedule. Available at https://hts.usitc.gov/search?query=2523.21.00.00.

79 USGS, Cement Statistic and Information, Minerals Yearbook (2022 and 2017). Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information.

80 World Integrated Trade Solution. (2023). "United States other hydraulic cements, etc exports by country in 2023." Available at https://wits.worldbank.org/trade/comtrade/en/country/USA/year/2023/tradeflow/Exports/partner/ALL/product/252390.

81 Id.

Figure 8: U.S. cement production and consumption (million metric tons)



Source: World Integrated Trade Solution. (2023). "United States other hydraulic cements, etc. exports by country in 2023." Available at https://wits.worldbank.org/trade/comtrade/en/country/USA/year/2023/tradeflow/Exports/partner/ALL/product/252390

2.6 Demand Projection

Global cement production in 2023 was estimated at 4,100 million metric tons by the U.S. Geological Survey[82] and is forecast to reach between 5,000 and 6,000 million metric tons by 2050.[83,84,85] In 2023, the United States produced 91 million metric tons of cement, or roughly 2 percent of global cement production.[86] By 2050, U.S. domestic cement production is expected to grow to an estimated 124 million metric tons, requiring new

[82] U.S. Geological Survey. 2024. "Mineral Commodity Summaries, January 2024" Available at: https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-cement.pdf.

[83] Cao, Z., Masanet, E., Tiwari, A., and Akolawala, S. 2021. "Decarbonizing Concrete: Deep decarbonization pathways for the cement and concrete cycle in the United States, India, and China" Industrial Sustainability Analysis Laboratory, Northwestern University. Available at: https://www.climateworks.org/wp-content/uploads/2021/03/Decarbonizing_Concrete.pdf.

[84] Cao, Z., Myers, R.J., Lupton, R.C. et al. 2020. "The sponge effect and carbon emission mitigation potentials of the global cement cycle" Nature Communications 11, 3777. Available at: https://doi.org/10.1038/s41467-020-17583-w.

[85] Global Cement and Concrete Association. 2020. "Concrete Future: The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete" Available at: https://gccassociation.org/concretefuture/wp-content/uploads/2022/10/GCCA-Concrete-Future-Roadmap-Document-AW-2022.pdf.

[86] U.S. Geological Survey. 2024. "Mineral Commodity Summaries, January 2024" Available at: https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-cement.pdf.

cement plants, according to a forecast by the Portland Cement Association and analysis by DOE.[87,88] The Portland Cement Association's forecast only accounts for capacity expansion from retrofits of existing facilities, but DOE suggests that greenfield development of alternative production methods will be possible by the 2030s, assuming they are demonstrated successfully in the late 2020s and receive appropriate policy support. Domestic cement demand, however, is expected to reach 150 million metric tons by 2050 for a shortfall of approximately 26 million metric tons.[89] Based on this cement production forecast, DOE also forecasted domestic clinker production for four scenarios with increasingly aggressive adoption of energy efficiency; fuel-switching; clinker substitution; and CCUS.[90]

Table 8 summarizes these forecasted production values in 2050, along with the assumed clinker-to-cement ratios being utilized in the given scenario.

Demand drivers: *Inflation Reduction Act*, *CHIPS Act*, and *Bipartisan Infrastructure Law*

The flurry of federal legislation to support clean energy development and spur new investment in industrial manufacturing is likely to be a new driver of domestic cement demand.

The *Inflation Reduction Act* (IRA) is expected to be a larger driver of demand for construction materials, including cement, particularly for renewable energy projects such as offshore and onshore wind and utility-scale solar. The IRA tax credits are expected to stay in place through 2032, unless altered by Congress. With substantial tax credits through 2032, declining resource costs, and increased commercial interest and demand for renewable and low-carbon resources, we can expect cement consumption to increase in line with increased energy development. For example, a 5 megawatt onshore wind turbine foundation, depending on industry codes and standards, can require up to 690 cubic meters of concrete or as much as 165 metric tons of cement;[91]

Table 8: Domestic cement and clinker production in 2050 forecast by the U.S. Department of Energy

Country of Origin	Unit	Business As Usual Scenario	Moderate Scenario	Advanced Scenario	Near Zero Scenario
Cement production in 2050	Million metric tons	123.6	123.6	123.6	123.6
Clinker production in 2050	Million metric tons	106.3	100.2	92.7	81.6
Clinker-to-cement ratio in 2050	–	0.86	0.81	0.75	0.66

Source: U.S. Department of Energy. (2022). "Industrial Decarbonization Roadmap" Available at: https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

87 Portland Cement Association. 2016. "Market Intelligence: Long-Term Cement Outlook" Available at: http://www2.cement.org/econ/pdf/long_term_report_2016f.pdf.

88 U.S. Department of Energy. 2023. "Pathways to Commercial Liftoff: Low-Carbon Cement" Available at: https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf.

89 U.S. Department of Energy. 2022. "Industrial Decarbonization Roadmap" Available at: https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

90 Carbon capture and storage (CCS) is a more common term but does not encompass utilization technologies.

91 DNV, "Foundation concrete voids: How to address the issue in wind turbine foundation." (Sept. 8, 2022) Available at: https://www.dnv.com/article/foundation-concrete-voids-229998/#:~:text=A%205%20MW%20turbine%20may,the%20on%2Dsite%20concrete%20placement.

many wind turbines will require more, particularly if the wind turbine is larger or requires a different foundation pad.[92] In 2023, an estimated 2,220 onshore turbines were installed in the United States, with a total estimated capacity of 6,600 megawatts.[93] Using the estimate above, these projects required approximately 366,000 metric tons of cement. Using the most ambitious projected growth rates for onshore wind, DOE estimates that because of IRA incentives, demand could reach 25 gigawatts by 2028. Using the estimate above, this could equate to as much 825,000 metric tons of additional cement demand annually by 2028 (0.9 percent of U.S. cement production).[94]

Large, utility-scale ground-mounted solar systems require concrete foot pads to support the steel tracking system and panels. The cement requirements for ground-mounted solar systems are substantially less than for onshore wind because they are not as high or heavy. Given the wide potential and varying nature of these installations, it is difficult to estimate how much cement demand can be attributed to the growth in domestic solar installations that will result from the IRA tax incentives. However, with a potential growth of domestic solar installations to as much as 1,000 gigawatts by 2035, it is reasonable to assume that domestic cement consumption will increase to meet the needs for utility-scale solar-PV foundations and supporting structures.[95] Finally, if the United States were to experience a nuclear industrial renaissance, either with traditional large reactor systems or new, state-of-the-art small modular reactors, we would expect cement demand to increase as a result. Historically, large (1,100 megawatts) pressurized water reactor nuclear plants required, on average, 190,000 cubic meters of concrete.[96] Experience with new advanced reactor designs is limited, but estimates suggest concrete use to be higher with substantial variation by reactor type.[97] Smaller modular units may only require 20,000 cubic meters of concrete, also varying by plant design, though would have comparable concrete use per megawatt of generation capacity.[98]

The *CHIPS* Act of 2022 and the IRA are already jumpstarting U.S. industrial manufacturing and renewable energy deployments.[99] In 2023, domestic construction spending on new manufacturing facilities more than doubled from 2022, with companies averaging $16.2 billion per month on building new manufacturing facilities. The $53 billion appropriated through the CHIPS Act has catalyzed semiconductor manufacturing investment throughout the country, with many of the new or expanded facilities located in Arizona, Texas, New York, and the Midwest.[100] One type of manufacturing facility is a foundry, or "fab", which is a multi-million square feet, high-tech facility that produces millions of semiconductor chips. According to Intel Corporation, a single new state-of-the-art fab requires an estimated 600,000 cubic meters of concrete or about 150,00 metric tons of cement (nearly 0.2 percent of U.S. cement production).[101] Close to a dozen new or expanded fabs have been announced since the *CHIPS Act*, potentially driving millions of tons of demand for cement in the United States.[102]

92 DNV, "Foundation concrete voids: How to address the issue in wind turbine foundation." (Sept. 8, 2022) Available at: https://www.dnv.com/article/foundation-concrete-voids-229998/#:~:text=A%205%20MW%20turbine%20may,the%20on%2Dsite%20concrete%20placement.

93 U.S. Geological Survey, Berkley Lab, American Clean Power, The U.S. Wind Turbine Database, https://eerscmap.usgs.gov/uswtdb/.

93 25 gigawatts is equivalent to 25,000 megawatts. Divided by 5 megawatts per turbine equals 5000 new turbines per year by 2028. Each turbine requires approximately 165 metric tons of cement for the foundation, totaling roughly 825,000 metric tons by 2028.

95 U.S. DOE, Solar Future Study (Sept. 8, 2021). Available at: https://www.energy.gov/eere/solar/solar-futures-study.

96 United Engineers and Constructors. 1988. "Phase 9 update (1987) report for the Energy Economic Data Base Program EEDB-IX" (No. DOE/NE–0091). Available at: https://www.osti.gov/biblio/7227212.

97 Per F. Peterson, Haihua Zhao, Robert Petroski, Metal and Concrete Inputs for Several Nuclear Power Plants, University of California, Berkeley, (Feb. 4, 2005). Available at: https://fhr.nuc.berkeley.edu/wp-content/uploads/2014/10/05-001-A_Material_input.pdf.

98 Id.

99 Niels Graham, "The IRA and CHIPS Act are supercharging US manufacturing construction," The Atlantic Council , Feb. 13, 2024.

100 Semiconductor Industry Association, U.S. Semiconductor Ecosystem Map, (last updated Mar. 28, 2024). Available at https://www.semiconductors.org/ecosystem/.

101 Intel Newsroom. "How a semiconductor factory works." Accessed 23 October 2024. Available at: https://www.intel.com/content/www/us/en/newsroom/tech101/manufacturing-101-how-semiconductor-factory-works.html#gs.gzd636.

102 Semiconductor Industry Association, U.S. Semiconductor Ecosystem Map, (last updated Mar. 28, 2024). Available at https://www.semiconductors.org/ecosystem/.

Finally, the *Infrastructure Investment and Jobs Act* (IIJA), also known as the *Bipartisan Infrastructure Law*, appropriated an estimated $300 billion to repair and upgrade U.S. roads, airports, ports, and public infrastructure through 2026.[103] These federal investments have contributed to steady recent upward demand for cement since 2021, but it is unclear how much of this demand was induced by new federal spending. While it is difficult to determine with certainty, the combined induced demand for cement that the IIJA, *CHIPS Act*, and IRA could result in several millions of tons of additional cement demand per year through the mid-2030s. Out of a current demand of 117 million metric tons of cement per year, the increased private demand from these three pieces of federal legislation of several million tons of cement for manufacturing and energy development could be a noticeable driver of demand.

103 American Concrete Pavement Association. 2022. "The Infrastructure Investment and Jobs Act: What's in it for the Concrete Pavement Industry?"

SECTION 3

Technology Pathways to Decarbonize Cement Production

The following section provides an overview of the leading technological pathways towards full abatement of cement sector emissions. Descriptions of each pathway include, where possible, a summary of the technology and its current Technology Readiness Level (TRL),[104] associated cost estimates and key technical considerations for adoption, and the potential contribution to decarbonizing the cement sector.

3.1 Plant Efficiency Upgrades

Today, one of the simplest, most cost-effective ways to reduce emissions is by improving energy efficiency. For example, optimizing how feedstocks enter and move through kilns can help stabilize kiln temperatures and reduce heat consumption, indirectly reducing nitrogen oxide and CO_2 emissions.[105] Other opportunities include improved thermal efficiency of the precalciner, improved electrical and mechanical efficiency of grinding equipment, and reducing the temperature of calcination through alternative feedstocks, discussed in **Section 3.2** below.[106] However, there is a diminishing availability of cost-effective measures for abating emissions with plant efficiency upgrades alone.[107,108] One study from the Royal Institute of International Affairs estimates that energy efficiency interventions based on currently deployable technologies have a maximum abatement potential of just 4–8 percent of cement production emissions globally, inclusive of waste and heat recovery.[109] Examples of such energy efficiency interventions include waste heat recovery through industrial heat pumps and combined heat and power generation, especially where co-location is possible within larger industrial clusters.[110]

104 Technology readiness levels are a framework developed by NASA for describing the maturity of an evolving technology to allow for consistent discussion across varying types of technology. See the following guide from the U.S. Department of Energy: https://www.directives.doe.gov/terms_definitions/technology-readiness-level.

105 U.S. EPA. 2008. 12.2 Coke Production. AP 42, Fifth Edition, Volume 1, Chapter 12. U.S. Environmental Protection Agency. Available at: https://www3.epa.gov/ttn/chief/ap42/ch12/final/c12s02_may08.pdf.

106 Rissman, J., 2024. *Zero-Carbon Industry: Transformative Technologies and Policies to Achieve Sustainable Prosperity*. Columbia University Press.

107 Griffiths, S., B. Sovacool, M. Bazilian, J. Kim, D. Furszyfer Del Rio, J. Uratani. 2023. "Decarbonizing the cement and concrete industry: A systematic review of socio-technical systems, technological innovations, and policy options" *Renewable and Sustainable Energy Reviews* 180 (2023) 113291. Available at: https://doi.org/10.1016/j.rser.2023.113291.

107 Griffiths, S., B. Sovacool, M. Bazilian, J. Kim, D. Furszyfer Del Rio, J. Uratani. 2023. "Decarbonizing the cement and concrete industry: A systematic review of socio-technical systems, technological innovations, and policy options" *Renewable and Sustainable Energy Reviews* 180 (2023) 113291. Available at: https://doi.org/10.1016/j.rser.2023.113291.

108 Benhelal, E., E. Shamsaei, M. Rashid. 2021. "Challenges against CO_2 abatement strategies in cement industry: A review" *Journal of Environmental Sciences* 104 (2021), 84-101, ISSN 1001-0742. Available at: https://doi.org/10.1016/j.jes.2020.11.020.

109 Lehne, J., F. Preston. 2018. "Making concrete change." Innovation in Low-carbon Cement and Concrete. Royal Institute of International Affairs. Available at: http://refhub.elsevier.com/S1364-0321(23)00147-8/sref34.

110 Madlool, N., R. Saidur, N. Rahim, M. Kamalisarvestani. 2013. "An overview of energy savings measures for cement industries." *Renew Sustain Energy Rev* 2013;19: 18–29. Available at: https://doi.org/10.1016/j.rser.2012.10.046.

While the Royal Institute's estimates only consider currently available energy efficiency interventions, DOE estimates that energy efficiency levers could have an unconstrained abatement potential of up to 20 percent compared to the business-as-usual scenario assuming energy efficiency technologies continue to advance in the coming decades.[111]

3.2 Alternative Feedstocks and Production Processes

DOE identifies alternative feedstocks and alternatives to traditional rotary kiln production as a viable track towards sector-wide emissions abatement which, along with CCUS technology, could have up to 60–70 percent abatement potential by 2050 compared to business as usual.112 Historically, the main feedstock for cement has been limestone, which is primarily composed of calcium carbonate. As described in **Section 2** above, the calcium is recovered through a high-temperature calcination process that rejects the carbonate as CO_2 gas, resulting in two distinct sources of CO_2 emissions: about a third comes from burning fuel to reach the appropriate calcination temperature within the kiln, and about two-thirds comes from the chemical reaction itself. Alternative feedstocks are aimed at reducing or eliminating the emissions from the chemical reaction, whereas alternative production processes are aimed at reducing or eliminating the emissions from the high-temperature calcination process.

Possible alternative feedstocks include calcium silicates, found in basaltic rocks abundant in the earth's crust; magnesium silicates, found in various minerals such as olivine and serpentine; and calcium-containing industrial waste products, such as steel and iron slag, coal fly ash, and various mining tailings.[113,114] On the process side, electrochemical cement production is an emerging alternative production process that utilizes a pH gradient to selectively dissolve and re-precipitate calcium from the feedstock at near room temperature, avoiding the need for a fossil-fired kiln altogether. One of the primary value propositions of this method is that it relies on established, readily available industrial electrochemical process technology in the form of an industrial-scale acid-base electrolyzer.[115]

The DOE's Office of Clean Energy Demonstrations (OCED) recently awarded two low-carbon cement startups with federal funding to build first-of-a-kind demonstration plants utilizing alternative feedstocks: Massachusetts-based Sublime Systems, and California-based Brimstone Energy.[116] Both companies produce cement and high-value co-products (such as iron oxide and magnesium oxide) from reactive calcium and silicates using calcium silicate feedstocks. Sublime Systems is further developing an electrochemical calcination process to fully avoid emissions from the traditional high temperature calcination process, which would result in true-zero process emissions.[117] Alternatively, Brimstone Energy aims to utilize the CO_2 adsorption properties of its magnesium co-product to partially offset the emissions from its kiln-based calcination process.[118] Sublime Systems and

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111 U.S. DOE. 2023. "Pathways to Commercial Liftoff: Low-Carbon Cement" Available at: https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf.

112 Ibid.

113 U.S. Department of Energy. 2022. "Industrial Decarbonization Roadmap" Available at: https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

114 Chen, Z., R. Lalit. RMI 2023. "The 3Cs of Innovation in Low-Carbon Concrete: Clinker, Cement, and Concrete". Available at: https://rmi.org/insight/innovation-in-low-carbon-concrete/.

115 Ellis, L., A. Badel, M. Chiang, Y. Chiang. 2019. "Toward electrochemical synthesis of cement—An electrolyzer-based process for decarbonating CaCO3 while producing useful gas streams" *Proceedings of the National Academy of Sciences 2019*, 117 (23) 12584-12591. Available at: https://doi.org/10.1073/pnas.1821673116.

116 U.S. DOE. "Industrial Demonstrations Program Selected and Awarded Projects: Cement and Concrete" 2024. Available at: https://www.energy.gov/oced/industrial-demonstrations-program-selected-and-awarded-projects-cement-and-concrete.

117 Sublime Systems. "Technology: true-zero (not net-zero) cement making for a post-carbon world" Available at: https://sublime-systems.com/technology/. Accessed 9 December 2024.

118 Brimstone Energy. "Technology: decarbonized, from rock to city block" Available at: https://www.brimstone.com/technology. Accessed 9 December 2024.

Brimstone Energy aim to complete construction of their demonstration plants and begin cement production as early as 2026, which would raise the TRL for alternative feedstocks and production processes to level 8 or 9.[119,120]

3.3 Clinker Substitution and Alternative Binder Chemistries

Clinker is the main constituent in most types of cement and is the material that reacts with water to allow cement to harden. Adjusting the ratio of clinker relative to other materials in the final cement mix can reduce emissions by stretching the same amount of emissions-intense clinker across more tons of finished product. The quantity of clinker used in cement is known as the clinker ratio and has important implications for the cement's finished properties. Blending in supplementary cementitious materials (SCMs) such as slag from iron and steel production, fly ash from coal-fired power plants, raw limestone, and other materials is common in the cement industry as a whole; however, the specific ratio of clinker varies, particularly among nations, due to regional availability of SCMs and different cement certification standards.

In the United States, cement producers generally adhere to the ASTM C-150 Standard set by the American Society for Testing and Materials, which defines clinker ratios and other chemical properties of U.S.-made cement varieties.[121,122] The average clinker ratio in the United States is 0.88, or 880 kilograms clinker per metric ton of cement.[123,124] By comparison, the world average is 0.76, and the ratio is between 0.64 and 0.76 in the European Union, India, and China.[125] In the near term, the expansion of cement varieties that offer the same building properties while reducing the clinker ratio offer one way to reduce, but not eliminate, the embedded emissions of each ton of cement. DOE estimates that substituting clinker with limestone, which today is already viable at TRL 9, could result in up to 15 percent emissions abatement, while emerging substitutes such as limestone calcined clay (LC3) and natural pozzolans have an abatement potential of up to 30 percent.[126]

DOE recently awarded funding to Colorado-based startup Terra CO_2 Technology for a new SCM manufacturing facility utilizing local mine tailings as a feedstock ($52.6 million from the Office of Manufacturing and Energy Supply Chains) and to Virginia-based Roanoke Cement Company for demonstrating the viability and validating the market demand for LC3 technology (up to $61.7 million from OCED).[127,128]

119 Sublime Systems. 2024. "Sublime Systems Selected by U.S. Department of Energy to Receive $87M Investment to Accelerate Commercial-Scale, True-Zero Cement Manufacturing Technology" Available at: https://sublime-systems.com/sublime-systems-selected-by-u-s-department-of-energy-to-receive-87m-investment-to-accelerate-commercial-scale-true-zero-cement-manufacturing-technology/

120 Brimstone. 2024. "Industrial Demonstrations Program Selects Brimstone for Transformational $189 Million Federal Investment to Decarbonize Cement Industry" Available at: https://www.brimstone.com/post/industrial-demonstrations-program-selects-brimstone-for-transformational-189-million-federal-invest.

121 Portland Cement Association. "Cement Types." Available at: https://www.cement.org/cement-concrete/concrete-materials/cement-types.

122 World Cement. 2020. "US Cement Standards: Accelerating the green transition." Available at: https://www.worldcement.com/special-reports/16042020/us-cement-standards-accelerating-the-green-transition/.

123 U.S. Geological Survey. 2024. "Cement Statistics and Information" Accessed 30 October 2024. Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information.

124 World Resources Institute. 2024. "The US Needs to Lower Cement Emissions — 'Blended Cement' Can Help." Available at: https://www.wri.org/insights/lower-carbon-blended-cement.

125 Global Cement and Concrete Association. 2024. "Getting the Numbers Right" Accessed 30 October 2024. Available at: https://gccassociation.org/sustainability-innovation/gnr-gcca-in-numbers/.

126 U.S. Department of Energy. 2023. "Pathways to Commercial Liftoff: Low-Carbon Cement" Available at: https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf.

127 U.S. DOE Office of Manufacturing and Energy Supply Chains. 2024. "Advanced Energy Manufacturing and Recycling Program Selections" Available at: https://www.energy.gov/mesc/advanced-energy-manufacturing-and-recycling-program-selections.

128 U.S. DOE Office of Clean Energy Demonstrations. 2024. "Industrial Demonstrations Program Selected and Awarded Projects: Cement and Concrete" Available at: https://www.energy.gov/oced/industrial-demonstrations-program-selected-and-awarded-projects-cement-and-concrete.

While clinker substitution changes the ratio of clinker to SCMs in the final cement blend, there are also alternative cement binder chemistries in development that shift away from traditional ordinary Portland cement clinker entirely. **Table 9** summarizes the six classes of clinker alternatives that have been piloted or demonstrated at small production scales (TRL 6–7) or are commercially available (TRL 8–9), along with their potential for reducing process emissions and thermal energy. While DOE estimates that alternative cement chemistries such as these could have an emissions abatement potential of up to 100 percent compared to business as usual, it also notes that these alternatives are far from technological maturity and require more research and demonstration before market adoption.[129]

3.4 Carbon Capture, Utilization, and Sequestration

CCUS refers to the capture of carbon emissions with two possible end uses: permanent sequestration, i.e., storage in underground geological formations, or utilization, i.e., used as a feedstock in a separate end product. Here, we use the acronym CCUS to refer generally to both types of carbon capture projects.

DOE projects that under a near-zero GHG emissions scenario, U.S. cement manufacturing GHG emissions can decrease to near zero by 2050, while cement production increases by nearly 50 percent. Between 60 and 70 percent of the total GHG emission reductions in this scenario are the result of CCUS and alternative feedstocks and production methods. Post-combustion CCUS can capture emissions from fuel combustion and thermal decomposition of limestone. DOE estimates the cost of amine-based post-combustion CCUS at a coal- and coke-fueled preheater/precalciner kiln to be from $25–55 per metric ton of cement higher than the $85 per metric ton 45Q tax credit.[130] Meanwhile, the Global Cement and

Table 9: Alternative clinker cements

Cement type	Process CO_2 reduction potential	Thermal energy reduction potential
Reactive belite cement (RB)	3.1%	8.2%
Belite-ye'elimite-ferrite cement (BYF)	29.1%	34.9%
Calcuim sulfoaluminate cement (CSA)	42%	46.9%
Carbonatable calcium silicate cement (CCSC)	24.8%	38.9%
Calcium hydrosilicate cement (CHS)	33.2%	50.6%
Magnesium oxides derived from magnesium silicates (MOMS)	100%	46.5%

Cao, Z., Masanet, E., Tiwari, A., and Akolawala, S. (2021). Decarbonizing Concrete: Deep decarbonization pathways for the cement and concrete cycle in the United States, India, and China. Industrial Sustainability Analysis Laboratory, Northwestern University. Available at: https://www.climateworks.org/report/decarbonizing-concrete/.

129 U.S. Department of Energy. 2023. "Pathways to Commercial Liftoff: Low-Carbon Cement" Available at: https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf.

130 Ibid.

Concrete Association reports that for the entire concrete industry CCUS accounts for 36 percent of all planned emissions reductions by 2050.[131] Pre-combustion carbon capture is a less mature technology and involves the removal of CO_2 from the fuel mix through gasification prior to limestone calcination. Given that over half of cement production emissions come from the thermal decomposition of limestone, pre-combustion CCUS is inherently less efficient and receives less consideration in literature compared to post-combustion methods.[132, 133]

The most mature post-combustion CCUS technology relevant to the cement industry today is the amine-based solvent method, in which CO_2 from the flue gas leaving the cement kiln is scrubbed in an adsorption column, followed by a heated desorption step to remove the CO_2 and regenerate the solvent.[134,135] Amine-based CCUS technology has already been demonstrated at commercial scale in the petrochemical and electricity sectors,[136] and notable amine-based CCUS cement facilities include Heidelberg Materials' Brevik CCS cement plant in partnership with the Norwegian government, slated to begin production of their "evoZero" cement in Q1 2025, and Anhui Conch's CCUS cement plant in Baimashan, China, the country's first fully integrated cement CCUS project that came online in 2018 with a capacity of 50,000 tonnes of cement per year.[137,138]

In the process of installing CCUS, given the sensitivity of market-ready amine CCUS technology to sulfur dioxide, it is very likely that further sulfur dioxide reductions—through additional scrubbing, or more likely through fuel-switching from coal to natural gas or an alternative fuel—would also be necessary. As a consequence of installing CCUS, sulfur dioxide emissions may be mostly eliminated.[139] Another important consideration of CCUS is the heat requirement for the sorbent regeneration step of the carbon capture process loop. As in the iron and steel industry, finding ways to repurpose waste heat for CCUS will be critical for preventing additional emissions from auxiliary heat and power that would otherwise be needed.[140,141,142] In this way, plant efficiency upgrades (**Section 3.1**) intersect with CCUS and further define the need for efficient heat recovery systems in modern cement plants.

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131 Global Cement and Concrete Association. 2020. "Concrete Future: The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete" Available at: https://gccassociation.org/concretefuture/wp-content/uploads/2022/10/GCCA-Concrete-Future-Roadmap-Document-AW-2022.pdf.

132 Cao, Z., Masanet, E., Tiwari, A., and Akolawala, S. 2021. "Decarbonizing Concrete: Deep decarbonization pathways for the cement and concrete cycle in the United States, India, and China." Industrial Sustainability Analysis Laboratory, Northwestern University. Available at: https://www.climateworks.org/wp-content/uploads/2021/03/Decarbonizing_Concrete.pdf.

133 International Energy Agency, World Business Council on Sustainable Development, and Cement Sustainability Initiative. 2018. "Technology Roadmap – Low-Carbon Transition in the Cement Industry." Available at: https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry.

134 Global Cement and Concrete Association. Post-Combustion Capture. Available at: https://gccassociation.org/cement-and-concrete-innovation/carbon-capture-and-utilisation/post-combustion-capture/.

135 Jiang, K., H. Yu, Z. Sun, Z. Lei, K. Li, L. Wang. "Zero-Emission Cement Plants with Advanced Amine-Based CO_2 Capture" Environ. Sci. Technol. 2024, 58, 16, 6978–6987. Available at: https://doi.org/10.1021/acs.est.4c00197.

136 Haffner, R. Power Engineers. 2024. "Solvent-Based Post Combustion Carbon Capture" Available at: https://www.powereng.com/library/solvent-based-post-combustion-carbon-capture. Accessed 1/2/2025.

137 Heidelberg Materials. "Brevik CCS – World's first CO_2-capture facility in the cement industry" Available at: https://www.brevikccs.com/en. Accessed 1/2/2025.

138 Global Cement and Concrete Association. 2024. "China begins operations at the world's largest oxy-fuel combustion CCUS project in cement sector" Available at: https://www.globalccsinstitute.com/news-media/insights/china-begins-operations-at-the-worlds-largest-oxy-fuel-combustion-ccus-project-in-cement-sector/. Accessed 1/2/2025.

139 Clean Air Task Force. 2023. Air Pollutant Reductions from Carbon Capture Report. Available at: https://www.catf.us/resource/air-pollutant-reductions-carbon-capture/.

140 Perpinan, J., et al. 2023. Integration of carbon capture technologies in blast furnace based steel making: A comprehensive and systematic review. Fuel 336, 127074 (2023). Available at: https://doi.org/10.1016/j.fuel.2022.127074.

141 Biermann, M., et al. 2019. *Excess heat-driven carbon capture at an integrated steel mill – Considerations for capture cost optimization*. International Journal of Greenhouse Gas Control 91, 102833 (2019). Available at: https://doi.org/10.1016/j.ijggc.2019.102833.

142 Zhang, Z., D. Vo, J. Kum, S. Hong, C. Lee. 2023. *Enhancing energy efficiency of chemical absorption-based CO_2 capture process with advanced waste-heat recovery modules at a high capture rate*. Chemical Engineering Journal 472, 144918 (2023). Available at: https://doi.org/10.1016/j.cej.2023.144918.

While DOE estimated CCUS to be between TRL 6 and 7.5 in 2023, carbon capture in the cement sector is close to commercial demonstration, with a handful of projects slated to begin procurement and construction in the next few years. The OCED recently awarded up to $500 million each to two cement companies to build commercial-scale carbon capture units at existing cement plants. Heidelberg Materials US plans to build an integrated carbon capture, transport, and storage system at its recently modernized cement plant in Indiana, with the goal of capturing at least 95 percent of plant CO_2 emissions and storing it within geologic formations beneath the plant itself. The National Cement Company of California plans to use its OCED funding to produce carbon-neutral cement utilizing a combination of three technology pathways: locally sourced biomass as an alternative fuel, substitution of clinker with LC3, and capture and sequestration of approximately 950,000 metric tons of CO_2 per year.[143] Holcim reports plans to build six CCUS projects across Europe and capture five million tons of CO_2 annually by 2030.[144] The Australia-based CCUS company Leilac is also leading the development of multiple pilot projects and engineering studies across the United States, Germany, Poland, and Australia, with plans to commence three CCUS projects with Cemex in 2025.[145,146] Among Leilac's current CCUS projects are a first-of-a-kind plant retrofit as well as a greenfield cement plant with integrated CCUS.[147]

3.5 Alternative Fuels

Fuel-switching from fossil fuels to alternative lower-carbon fuels presents an opportunity for emissions abatement in all heavy industries, but the cement sector stands out in this regard due to the particular difficulty of direct electrification of cement production processes. Some amount of fuel-switching will likely be necessary for medium-term decarbonization goals while emerging process technologies develop. The U.S. Geological Survey reported that in 2022, the cement industry's energy consumption was made up of 47 percent coal and petcoke, 24 percent natural gas, 16 percent waste fuels, and 13 percent purchased electricity,[148] while the Portland Cement Association reported an industry-wide desire to diminish coal and petcoke use to 10 percent or less by 2050.[149] Examples of technologically mature alternative fuels are waste fuels and biomass. Both of these are considered at TRL 9 by DOE and are deployable with minimal cost impacts (0–5 $/ton cement), but they have limited emissions abatement potential (1–8 percent relative to business as usual).[150] Low-carbon hydrogen is another option for fuel-switching but presents an infrastructure obstacle in which major plant overhauls or retrofits would be necessary to utilize hydrogen at greater than approximately 20 percent of the fuel mix by volume.[151] High ratios of low-carbon hydrogen to fossil fuel feedstocks would be required to obtain meaningful GHG emission reductions and utilizing hydrogen as

143 U.S. DOE Office of Clean Energy Demonstrations. 2024. "Industrial Demonstrations Program Selected and Awarded Projects: Cement and Concrete." Available at: https://www.energy.gov/oced/industrial-demonstrations-program-selected-and-awarded-projects-cement-and-concrete.

144 Holcim. 2023. "2023 Climate Report." Available at: https://www.holcim.com/sites/holcim/files/2024-04/28022024-holcim-climate-report-2023.pdf.

145 Cemex. 2023. "2023 Integrated Report" Available at: https://www.cemex.com/documents/d/cemex/cemex-2023-integrated-report-en.

146 Leilac. 2024. "Leilac Projects." Accessed 30 October 2024. Available at: https://www.leilac.com/projects/.

147 Leilac. 2021. "Leilac Roadmap 2050" Available at: https://www.leilac.com/wp-content/uploads/2022/09/LEILAC-Roadmap.pdf.

148 USGS. 2024. "Cement 2022 tables-only release." Minerals Yearbook 2022, v. I, Metals and Minerals. Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information.

149 Portland Cement Association. 2021. "Roadmap to Carbon Neutrality" Available at: https://www.cement.org/wp-content/uploads/2024/05/Roadmap_Jan2024.pdf.

150 U.S. DOE. 2023. "Pathways to Commercial Liftoff: Low-Carbon Cement" Available at: https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf.

151 European Cement Research Academy (ECRA). 2022. "Technology Paper No. 18: Use of hydrogen as fuel." Available at: https://ecra-online. org/fileadmin/redaktion/files/pdf/ECRA_Technology_Papers_2022.pdf.

the sole fuel mix for high temperature industrial heat applications remains at low- to mid-TRL which requires further development.[152,153]

Examples of major cement companies already beginning to transition to alternative fuels include Cemex, which reported using 37 percent alternative fuels in its processes in 2023 and pledged to reach 55 percent by 2030, and Holcim, which pledged to operate all of its European plants with 90 percent alternative fuels by 2030.[154,155]

3.6 Decarbonized Electricity

Decarbonized electricity as a viable pathway for decarbonized cement production relies on the availability of electric unit operations. Plant efficiency upgrades with electrified industrial heat pump technology is already available (see **Section 3.1**), and alternative production processes such as using renewable electricity to power electrochemical cement production is a rapidly emerging technology pathway (see **Section 3.2**). Electrified process equipment such as precalciners and rotary kilns are another set of emerging technologies that still rely on the traditional high-temperature calcination process while avoiding emissions from fuel combustion. DOE estimates these technologies have an unconstrained emissions abatement potential of up to 35 percent compared to business as usual and classifies these technologies with a TRL of 5–6, with electric precalciners representing the higher end of the TRL range due to its lower temperature requirement compared to electric kilns.[156]

VTT Decarbonate in Finland unveiled the first electric rotary kiln prototype in 2022.157 The unit still produces CO_2 and heat, resulting in nitrogen oxide emissions, but it avoids all emissions related to fuel combustion. The project may also begin capturing CO_2 in the future. Additionally, two cement companies, Cemex and UltraTech Cement, have signed memorandums of understanding with Finland-based company Coolbrook for construction of an industrial-scale pilot of its proprietary Roto Dynamic Heater, with claims of being capable of reaching up to 1700 °C.[158,159] Successful demonstration of these electric kilns would bring the TRL for this emerging pathway up to level 8 or 9.

3.7 Biocement or Microbially Induced Calcium Carbonate Precipitation

An emerging technology pathway to reduce lifecycle emissions from cement production is the use of various microbially-induced calcium carbonate precipitation (MICP) techniques, often referred to as biocement, that trap the CO_2 into the microscopic structure of the finished concrete rather than releasing it into the atmosphere. This technique aims to avoid thermal process emissions by skipping the pyro-processing step completely. There have been several techniques explored since the early 1990s, when the MICP process was patented to repair cracks and crevices in ornamental stone and concrete.[160,161] These processes are sometimes referred to as self-healing concrete, or concrete that

152 Griffiths S., B. Sovacool, J. Kim, M. Bazilian, J. Uratani. 2021. "Industrial decarbonization via hydrogen: a critical and systematic review of developments, socio-technical systems and policy options" Energy Res Social Sci 2021;80: 102208. Available at: https://doi.org/10.1016/j.erss.2021.102208.

153 Griffiths, S., B. Sovacool, M. Bazilian, J. Kim, D. Furszyfer Del Rio, J. Uratani. 2023. "Decarbonizing the cement and concrete industry: A systematic review of socio-technical systems, technological innovations, and policy options" Renewable and Sustainable Energy Reviews 180 (2023) 113291. Available at: https://doi.org/10.1016/j.rser.2023.113291.

154 Cemex. 2023. "2023 Integrated Report." Available at: https://www.cemex.com/documents/d/cemex/cemex-2023-integrated-report-en.

155 Holcim. 2023. "2023 Climate Report." Available at: https://www.holcim.com/sites/holcim/files/2024-04/28022024-holcim-climate-report-2023.pdf.

156 U.S. Department of Energy. 2023. "Pathways to Commercial Liftoff: Low-Carbon Cement." Available at: https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf.

157 Katajisto, O. "Cement precalcination with electricity and carbon dioxide sequestration." Presentation at VTT, May 25, 2022. Available at: https://www.decarbonate.fi/wp-content/uploads/2022/05/2022-05-17-Betonitutkimusseminaari.pdf.

158 International Energy Agency. "Tracking Cement." Accessed 29 October 2024. Available at: https://www.iea.org/energy-system/industry/cement.

159 Cemex. 2022. "CEMEX and Coolbrook electrify cement production process.“ Available at: https://www.cemex.com/w/cemex-and-coolbrook-electrify-cement-production-process.

can repair cracks autogenously or autonomously over time.[162] There is cutting-edge research into new bacteria, such as cyanobacteria that only requires light to drive a photosynthetic reaction in which the CO_2 from the clinker is bound in the material itself.[163] The cyanobacteria reacts with water and sunlight to form micro-structures known as stromatolites from the precipitated limestone, trapping the CO_2 within the molecular structure.

MICP and other biocement processes are still relatively nascent in their development beyond particular niche applications such as concrete repairs. However, there is emerging research to overcome hurdles to improve commercial scalability and ensure that biocements meet the performance criteria of traditional products.[164] There are at least two emerging startups working to commercialize biocement based processes. Prometheus Materials is focused on pre-fabricated cement blocks made using cyanobacteria pathways.[165] BioMason patented a bacterial biological process and claims that its process reduces the lifecycle emissions of cement by as much as 90 percent.[166] These remain new technologies that are likely far down the commercialization ladder; nevertheless, they offer a potential pathway to dramatically reduce cement lifecycle emissions.

3.8 Concrete Recarbonation and Circularity Options

Whereas limestone is decarbonated during the cement production process, concrete has a natural tendency to recarbonate during the setting and hardening phase, and it continues to slowly recarbonate over the course of its lifetime. In this way, concrete can act as a natural sink of CO_2 emissions—approximately 45 percent of the process CO_2 from thermal decomposition after 20 years and 47 percent after 40 years.[167] However, recarbonation within concrete mixes is generally harmful to the structural strength of the finished product. Various cement industry decarbonization roadmaps cite concrete recarbonation as a major emissions reduction pathway for achieving 2050 climate goals.[168,169,170] There have been limited studies into this phenomenon and more research is needed to leverage recarbonation to its fullest extent.[171,172]

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160 Adolphe, J. P., Loubière, J. F., Paradas, J., and Soleilhavoup, F. (1990) *Procédé Detraitement Biologique d'une Surface Artificielle.* París: Francia European Patent 90400G97.0. (after French patent 8903517, 1989).

161 Castro-Alonso MJ et al. "Microbially Induced Calcium Carbonate Precipitation (MICP) and Its Potential in Bioconcrete: Microbiological and Molecular Concepts." *Frontiers in Materials*. (2019) 6:126. doi: 10.3389/fmats.2019.00126.

162 ScienceDirect. "Self Healing Concrete." Accessed 29 October 2024. Available at: https://www.sciencedirect.com/topics/engineering/self-healing-concrete#:~:text=Self%2Dhealing%20concrete%20is%20mostly,its%20relatively%20low%20tensile%20strength.

163 Fraunhofer-Gesellschaft Institute. 2024. "Bio-concrete and biogenic construction materials with cyanobacteria." Accessed 24 October 2024. Available at: https://www.fraunhofer.de/en/press/research-news/2024/july-2024/bio-concrete-and-biogenic-construction-materials-with-cyanobacteria.html.

164 Atsu Kludze, et al. "Biocement from the ocean: Hybrid microbial-electrochemcial mineralization of CO_2." iScience, October 21, 2022. https://www.sciencedirect.com/science/article/pii/S2589004222014286.

165 Ben Dreith, "Prometheus Materials uses algae-based cement to make masonry blocks." Dezeen, Jun. 7, 2022. Available at: https://www.dezeen.com/2022/06/07/prometheus-biocomposite-cement-blocks/

166 Alliance for Low-Carbon Cement & Concrete, "Revolutionising cement with biotechnology – Biomason." Available at: https://alliancelccc.com/story/biomason/.

167 Xi, F., Davis, S.J., Ciais, P., Crawford-Brown, D., Guan, D., Pade, C., Shi, T., Syddall, M., Lv, J., Ji, L. and Bing, L., 2016. "Substantial global carbon uptake by cement carbonation." *Nature Geoscience*, 9(12), pp.880-883.

168 Global Cement and Concrete Association. 2020. "Concrete Future: The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete." Available at: https://gccassociation.org/concretefuture/wp-content/uploads/2022/10/GCCA-Concrete-Future-Roadmap-Document-AW-2022.pdf.

169 Holcim. 2023. "2023 Climate Report." Available at: https://www.holcim.com/sites/holcim/files/2024-04/28022024-holcim-climate-report-2023.pdf.

170 Cemex. 2023. "2023 Integrated Report." Available at: https://www.cemex.com/documents/d/cemex/cemex-2023-integrated-report-en.

171 Griffiths, S., B. Sovacool, M. Bazilian, J. Kim, D. Furszyfer Del Rio, J. Uratani. 2023. "Decarbonizing the cement and concrete industry: A systematic review of socio-technical systems, technological innovations, and policy options." *Renewable and Sustainable Energy Reviews* 180 (2023) 113291. Available at: https://doi.org/10.1016/j.rser.2023.113291.

172 Cao, Z., Myers, R.J., Lupton, R.C. et al. 2020. "The sponge effect and carbon emission mitigation potentials of the global cement cycle." *Nature Communications* 11, 3777. Available at: https://doi.org/10.1038/s41467-020-17583-w.

With funding from the French government, Holcim led a collaborative research effort into concrete recarbonation known as FastCarb, which was aimed at studying the phenomenon to find more marketable uses while maintaining the necessary strength requirements.[173] These studies culminated in two industrial-scale demonstrations and a paper that outlines major findings, namely that the emissions abatement potential of this technology is only viable in specific scenarios where recycled concrete aggregates can be re-used on site instead of being transported to another location via truck.[174]

In contrast to the spontaneous recarbonation phenomenon discussed above, there has also been research into direct carbonation of concrete through CO_2 injection, also known as carbon mineralization. A handful of companies are working on breakthrough novel processes in this field that could also substantially bolster CCUS efforts by providing another viable sink for captured CO_2. CarbonCure Technologies, based in Nova Scotia and with mostly private funding, has provided more than 60 million cubic yards of directly carbonated concrete to projects across two dozen countries,[175] and Texas-based Solidia Technologies is developing a non-hydraulic cement formulation that utilizes high-purity CO_2 mineralization to reduce kiln emissions by 30 percent relative to standard ordinary Portland cement clinker production.[176]

3.9 Concrete End-Use Design Optimization and Construction Site Efficiencies

In the technology pathways discussed above, most of the burden for decarbonization lies with the producers of cement, from the massive multinational cement corporations to the small startups developing breakthrough technologies. Optimization of concrete end use and efficient design in construction projects are important demand-side levers for reducing emissions in the cement industry. These emissions reductions primarily depend upon building owners and designers, construction companies, and other end-users of concrete. The Mission Possible Partnership (including RMI and the World Economic Forum) estimate that by reducing overall demand for concrete, efficiency in design and construction could reduce industry-wide cement emissions by up to 22 percent by 2050 compared to business as usual.[177] These levers include topology optimization, lean design, alternative structural solutions, reuse of concrete elements, and building lifetime extension. The general principal behind these pathways is that many concrete structures are "over-designed" with far more concrete than is necessary, or they are demolished for reasons other than structural degradation. As such, the lowest-cost construction site efficiency solutions are lean design (using automated or machine-learning-based methods for minimizing the amount of concrete needed to achieve appropriate structural integrity) and building lifetime extension (limiting the demolition of existing building stock to reduce the need for new concrete builds).[178,179,180] These design optimizations and construction-site efficiencies also apply to roads, bridges, and any other construction projects that involve concrete.

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173 Holcim. 2021. "Paving the way to truly circular concrete with recarbonation." Accessed 30 October 2024. Available at: https://www.holcim.com/who-we-are/our-stories/paving-way-truly-circular-concrete-recarbonation.

174 Torrenti, J., et al. 2022. "The FastCarb project: Taking advantage of the accelerated carbonation of recycled concrete aggregates." *Case Studies in Construction Materials* 17 (2022) e01349. Available at: https://doi.org/10.1016/j.cscm.2022.e01349.

175 CarbonCure Technologies. "Carbon Cure." Accessed 31 October 2024. Available at: https://www.carboncure.com/news/carboncure-achieves-half-million-metric-tons-of-carbon-savings/.

176 Solidia Technology. "Cement and Concrete Technology Engineered for Greener Businesses." Accessed 31 October 2024. Available at: https://www.solidiatech.com/technology/.

177 Mission Impossible Partnership. 2023. "Making Net Zero Concrete and Cement Possible " Available at: https://www.missionpossiblepartnership.org/making-net-zero-concrete-and-cement-possible-report/.

178 Ibid.

179 Daehn, K., et al. 2022. "Innovations to decarbonize materials industries" Nature Reviews: Materials 7, 275-294 (2022). Available at: https://doi.org/10.1038/s41578-021-00376-y.

180 Scrivener, K., et al. 2018. "Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry" *Cement and Concrete Research* 114, 2-26. Available at: https://doi.org/10.1016/j.cemconres.2018.03.015.

SECTION 4

Adoption Strategies

There is an emerging ecosystem of legislation, federal and state policy support, and public-private investment that could dramatically reduce emissions within the cement sector to align with mid-century goals. In this report, we refer to these broadly as low-carbon cement *adoption strategies*. Between 2021 and 2024, there was a flurry of activity, largely tied to the passage and implementation of the IIJA and the IRA, to jumpstart industrial decarbonization. These policies and programs address the entire technology-to-market pipeline, from research, development, and deployment (RD&D) to early market commitments to full market penetration for new industrial decarbonization technologies. These adoption strategies are cultivated by many participating federal and state agencies, national and university labs, national standards organizations and certification processes, and corporate agreements and partnerships. They represent varied, and at times conflicting, visions for the future of the industry.

In this section, we first describe the existing tapestry of enacted policies, focusing on those from the last four years. We next discuss the potential for new federal and state legislation and policy support for cement decarbonization that could catalyze greater technology investment and ultimately reduce sectoral emissions in line with mid-century targets. The adoption strategies detailed below include federal and state government use of low-carbon cement as well as private investment in lower-carbon technologies. There exists a panoply of low-carbon cement adoption strategies, but little evaluation of which strategies are most likely to succeed and little effort to advance an implementation framework. Further, the available literature generally does not map or prioritize those efforts across the technology-to-market pipeline. This whitepaper provides a systematic survey of existing and proposed policies, incentives, programs, and regulations to support the adoption of decarbonized cement (including policy design approaches, target technology pathways, appropriate implementation framework, and probability of success).

The **Policy Matrix** summarizes each adoption strategy, organized by the development stage (RD&D through market maturity). It also identifies an implementation framework that describes the pathway to adoption. Finally, it characterizes the probability of success using five factors.

4.1 Environmental Product Declarations and Labeling

Environmental Product Declarations

Environmental product declarations (EPD) provide detailed product information related to resource use, GHG and other emissions, waste generation, and other environmental impacts of a product from cradle to gate.[181] Ensuring that low-carbon cement is in actual fact, low-carbon, is critical to developing a robust market for these products as states and federal contractors open themselves up to potential risk and liability should they claim a grant or credit for low-carbon construction materials that do not meet required emission thresholds. Low-carbon cement is likely to be priced at a premium for some time. Therefore, developing a trusted process for transparent and verifiable lifecycle EPDs and easy-to-understand labeling of low-carbon construction materials is critical to driving further investment and assuring customers that the products they are using are in fact less carbon-intensive. Thus, requiring EPD reporting is a foundational policy that can help enable other decarbonization pathways and adoption strategies.

181 “Cradle to gate” refers to the emissions associated with manufacturing and upstream activities, up to the factory gate. It excludes downstream emissions associated with use, transportation, and disposal.

The first EPDs were developed in 1998 to measure emissions in manufacturing associated with hydroelectric facilities in Norway. They have increased in use and sophistication over the past three decades, with the International Organization of Standardization (ISO) providing detailed standards and methodology for verifying an EPD. These are governed by ISO 14025 and are referred to as Type III claims, as distinguished from Type I (Eco-labeling programs such as EnergyStar) and Type II (manufacturers' self-declaration with no third-party verification). Type III claims require quantification of environmental data and third-party verification.[182] EPDs can be either industry- or product-specific. Industry-specific EPDs provide the least-specific data given that they are intended to capture a wide swath of products, but can provide insights into the typical environmental impact of a product.[183] The Portland Cement Association provide industry-average EPDs for several cement products, such as Portland cement.[184] Industry-specific EPDs are valid for five years but are often updated more regularly.[185] Product-specific and third-party-certified EPDs are considered the most useful Type III EPD given that they are subject to the most vigorous verification and provide the greatest detail on specific environmental impact of the product. The concrete and cement industry is a leader in development of product-specific EPDs given the availability of such tools as Climate Earth's Ready Mix EPD Generator and efforts by the National Ready Mixed Concrete Association to support and popularize EPDs. **Figure 9** provides an example of a product- and plant-specific EPD.[186] It details the cradle-to-gate global warming potential from one metric ton of cement as produced at a Heidelberg Materials facility in Alabama. These easy-to-read and clear product-specific EPDs are useful for making procurement decisions that require materials' emission disclosure or preference for less-carbon intensive products.

Use of EPDs in state contracting is still limited, however. A 2022 survey of 35 state departments of transportation (DOTs) indicating that only five states have legislation that requires EPD submittals for state-funded projects.[187] This includes California, Colorado, Minnesota, New York, and Oregon, which have all adopted legislation requiring that the state transportation departments include and require EPDs for state-funded procurements.[188] New York State, for example, passed the Buy Clean Concrete guidelines in 2022 as required by State Finance Law 135-d which will require, starting in 2025, that all concrete mixes have an EPD if used in state-funded projects.[189]

182 Fuhler, Megan, et al. 2023. *The Importance of Environmental Product Declarations in the Decarbonization Effort.* Engineer Research & Development Center, U.S. Army Corps of Engineers, at 5. Available at: https://apps.dtic.mil/sti/trecms/pdf/AD1214338.pdf.

183 Id. at 6.

184 PCA. 2020 (revised 2023). Environmental Product Declaration, Portland Cement. Available at: https://www.cement.org/wp-content/uploads/2024/07/pca_epd_portland_athena_final_revised_nov2023-1.pdf.

185 PCA. Quantifying Environmental Impact. Available at: https://www.cement.org/a-sustainable-future/reaching-our-goal/quantifying-environmental-impact/.

186 Heidelberg Materials. 2022. Environmental Product Declaration for Cement. Available at: https://www.nrmca.org/wp-content/uploads/2022/11/LEEDS_CementPlantEPD_Final2022-11-09.pdf.

187 National Concrete Consortium. 2022. *NCC Spring 2022 State Reports on Sustainability and Concrete Materials,* at 20. Available at: https://cdn-wordpress.webspec.cloud/intrans.iastate.edu/uploads/2022/04/05-Miller-State-Reports.pdf.

188 FHWA. 2023. Environmental Product Declarations Help Create Sustainable Highways. Available at: https://www.fhwa.dot.gov/innovation/innovator/issue98/page_02.html#:~:text=States%20such%20as%20California%2C%20Colorado,with%20lower%20embodied%20GHG%20emissions.

189 New York State, Office of General Services, NYS Buy Clean Concrete Guidelines. https://ogs.ny.gov/nys-buy-clean-concrete-guidelines-0#:~:text=The%20NYS%20Buy%20Clean%20Concrete,deemed%20appropriate%20by%20the%20office.

Figure 9: Example Environmental Product Declaration

GENERAL INFORMATION

This cradle to gate Environmental Product Declaration covers two cement products produced at the Leeds Cement Plant. The Life Cycle Assessment (LCA) was prepared in conformity with ISO 21930, ISO 14025, ISO 14040, and ISO 14044. This EPD is intended for business-to-business (B-to-B) audiences.

Heidelberg Materials

Leeds Cement Plant and Terminal
8401 Second Avenue
Leeds, AL 35094

NRMCA CERTIFIED EPD

PROGRAM OPERATOR

National Ready Mixed Concrete Association
900 Spring Street
Silver Spring, MD 20910
https://nrmca.org/

NRMCA EPD #:20070

DATE OF ISSUE

November 11, 2022 (valid for 5 years until November 11, 2027)

Environmental Impacts

Leeds Plant: Product-Specific Type III EPD

Declared Cement Products (four):
Type IL; Type I-II

Declared Unit: One metric tonne of cement

	Cement Products Type IL (ecocem PLC)	Cement Products Type I-II
Global Warming Potential (kg CO_2-eq)	**867**	**920**
Ozone Depletion Potential (kg CFC-11-eq)	2.76E-05	2.88E-05
Eutrophication Potential (kg N-eq)	0.94	0.98
Acidification Potential (kg SO^2-eq)	2.60	2.74
Photochemical Ozone Creation Potential (kg O_3-eq)	60.4	63.9
Abiotic Depletion, nonfossil (kg Sb-eq)	1.6-E-04	1.65E-04
Abiotic Depletion, fossil (MJ)	676	710
Product Components:		
Clinker	84%	93%
Limestone, Gypsum and Others	16%	7%

Additional detail and impacts are reported on page 5

Heidelberg Materials. (2022). Environmental Product Declaration for Cement. Available at: *https://www.nrmca.org/wp-content/uploads/2022/11/LEEDS_CementPlantEPD_Final2022-11-09.pdf.*

Environmental Labeling

Section 60116 of the IRA appropriated $100 million through 2026 to EPA to develop and carry out, in consultation with the Federal Highway Administration and U.S. General Services Administration (GSA), a voluntary low-embodied carbon labeling program for construction materials.[190] The legislative intent is for EPA to develop a labeling scheme for construction materials used by both the federal and state governments and private entities that identifies materials “that have substantially lower levels of embodied GHG emissions associated with all relevant stages of production, use, and disposal as compared to estimated industry averages of similar materials or products.”[191] EPA is tasked with designating what the national and regional industry thresholds are for categories and sub-categories of construction materials, developing a tiered system to compare less carbon-intensive alternatives to the threshold, and a labeling system to signal to the market. EPA previously noted that it would begin with concrete and cement, asphalt, steel, and glass before moving onto other construction materials such as aluminum.

190 P.L. 117-169, § 60116.

191 P.L. 117-169, § 60116(a).

The labeling program is intended to complement ongoing industry EPD efforts. Under Section 60112 of the IRA, the EPA is to provide grants, direct technical assistance, and other resources to help manufacturers measure the embodied carbon in their materials and products and disclose this data through environmental product declarations. These initiatives can assist manufacturers in qualifying their materials and products for the labeling program. Furthermore, the labeling program aims to aid other stakeholders—such as architects, engineers, planners, contractors, suppliers, and construction and demolition firms—in making informed decisions.[192]

In August 2024, EPA indicated that it expects to rely on a three-phase process to standardize the quality of data used, set thresholds for the global warming potential (GWP) of different product and sub-product categories, and finally, develop labeling processes for products that meet EPA's thresholds.[193] First, EPA aims to improve publicly available EPDs and product category rules to better inform the lifecycle analysis process. This will help properly categorize construction materials and provide data for use in setting national and regional thresholds as well as determining how a product compares. The statute only requires that low-embodied carbon materials have emissions that are "substantially lower." EPA is proposing three-tiered labeling criteria and thresholds for products that will be reviewed and updated approximately every two to four years, depending on market conditions and available data (see **Table 10**).[194]

Importantly, EPA previously noted it would not apply broad or blanket eligibility criteria to materials but rather use product category rules, regional differences, and performance-based criteria to develop several tiers and thresholds within product categories. For cement, as noted above, there are diverse types for different end-use applications. Additionally, regional variations impact both the embodied carbon emissions and the performance standards of the cement. It is unclear at this time how exactly EPA will account for regional differences (state-by-state or broader regional differences), although it does acknowledge that it aims to use available data to "determine how significant regional differences within each material category [are], as well as how to best address regional differences within the United States in the threshold setting process."[195] A tiered eligibility format that captures the many regional and end-use applications for cement is likely to provide the market greater clarity and specificity as to the embodied carbon intensity of products and how they compare to industry standards.

Table 10: Possible label program eligibility criteria under a tiered format

Tier	Eligibility Criteria
Best	Product GWP must be under a value that represents the cutting edge of low-embodied-carbon products available in the market.
Better	Product GWP must be under a value that is lower than an industry and/or regional average product GWP but is higher than the "best" product GWP value.
Good	Product GWP must be under a value that is lower than an industry and/or regional average product GWP but is higher than the "better" product GWP value.

Source: U.S. EPA, Office of Chemical Safety and Pollution Prevention. (2024). "Implementation Approach for the U.S. EPA Label Program for Low Embodied Carbon Construction Materials," at 3. Available at: https://www.epa.gov/system/files/documents/2024-08/lpa_final_8-6-24.pdf.

192 U.S. EPA, Office of Chemical Safety and Pollution Prevention. 2024. "Implementation Approach for the U.S. EPA Label Program for Low Embodied Carbon Construction Materials," at 3. Available at: https://www.epa.gov/system/files/documents/2024-08/lpa_final_8-6-24.pdf.

193 Id.

194 Id. at 15.

195 Id. at 14.

In Phase 3, EPA previously noted it would develop simple, easy-to-read-and-understand labeling for materials. EPA will also create and maintain a public web registry for labeled products to allow users to make comparisons within the same product categories and to provide information on the labeled products. EPA previously noted it expected that a product would be able to move through the process in as little as 18 months, although it could take as long as four years.[196] The agency anticipates that initial products could be labeled as soon as September 2026.

4.2 Recent Federal Legislation and Agency Programs

Bipartisan Infrastructure Investment and Jobs Act

The 2021 IIJA is a sweeping $1.2 trillion infrastructure bill intended to upgrade the nation's roads, bridges, railways, broadband, water, and sewage systems. While much of the target infrastructure is highly cement-intensive construction, the IIJA did not create separate appropriations to support low-carbon cement deployment. However, IIJA did include a broad suite of crosscutting policies aimed at spurring development and deployment of lower-carbon alternative materials and support for industrial polices to do so. Most relevant here are the new offices that the IIJA created within DOE, such as OCED[197] and the Sustainable Manufacturing Initiative,[198] to support early-stage RD&D and technologies as they move through the technology-to-market pipeline.

DOE's $6.3 billion Industrial Demonstrations Program (IDP) funds deployment of decarbonization technologies that are beyond early-bench scale but not commercialized. The IDP announced in August 2024 that six cement projects had been selected for up to $1.6 billion in matching federal investment.[199] The projects fall into three broad technology buckets: substitution of clinker for less carbon-intensive clay or calcinated materials; CCUS; and first-of-a-kind validation and demonstration of new cement production technologies and chemistries.

IDP awarded $277 million to two projects that will use relatively proven methods to substitute clinker with widely available clays.[200] Another awarded project will receive up to $500 million to construct an integrated carbon capture, transport, and storage system at a newly modernized cement facility owned by Heidelberg Materials in Mitchell, Indiana.[201] Finally, to support first-of-a-kind technologies, OCED awarded funding to two early-stage demonstration projects to validate their cement production process and demonstrate commercialization at scale: up to $189 million to support Brimstone Energy's calcium silicate process with a combined capacity of 140,000 metric tons of ordinary Portland cement a year and up to $87 million for Sublime Systems to build a new facility to electrochemically produce calcium silicate-based ordinary Portland cement.[202] OCED's strategy seeks to derisk the portfolio of cement decarbonization technologies by investing in several pathways across multiple companies, both established (Heidelberg Materials) and more early-stage companies (Brimstone and Sublime). These technology strategies range in their degree of carbon emission reduction potential, with OCED investing simultaneously in different pathways. Clinker substitution with calcined clay has the potential to partially reduce emissions whereas CCUS and alternative cement production technologies could potentially eliminate industry emissions.

196 Id. at 19.

197 P.L. 117-58, § 41201.

198 P.L. 117-58, § 40522.

199 U.S. DOE. 2024. "Industrial Demonstrations Program Selected and Awarded Projects: Cement and Concrete." Available at https://www.energy.gov/oced/industrial-demonstrations-program-selected-and-awarded-projects-cement-and-concrete.

200 OCED – Industrial Demonstration Program. 2024. Calcined Clay Production for Limestone Calcined Clay Cement. Available at https://www.energy.gov/sites/default/files/2024-10/Factsheet_IDP_RoanokeCementCompany_PhaseOne_10.16.24.pdf.

201 OCED – Industrial Demonstration Program. 2024. Mitchell Cement Plant Decarbonization Project. Available at https://www.energy.gov/sites/default/files/2024-08/Factsheet_IDP_Heidelberg_8.14.24FINAL.pdf.

202 U.S. DOE. 2024. "Industrial Demonstrations Program Selected and Awarded Projects: Cement and Concrete." Available at: https://www.energy.gov/oced/industrial-demonstrations-program-selected-and-awarded-projects-cement-and-concrete.

Inflation Reduction Act

The 2022 IRA included a broad suite of provisions that is likely to spur greater adoption of low-carbon cement and concrete in federal and state public works projects; it also includes incentives and programs such as enhanced CCUS tax credits to increase investment in low-carbon industrial pathways. Additionally, the IRA appropriated roughly $2.15 billion through 2026 for the GSA's Federal Buildings Fund for use of low-carbon materials (see **Section 4.3**).[203] This additional funding for the Federal Buildings Fund is for construction materials that have substantially lower lifecycle GHG emissions. The IRA also provided an additional $975 million to GSA to support emerging and sustainable building materials technology.[204]

Perhaps the most substantial IRA investment in low-carbon cement is the $2 billion appropriated to the Federal Highway Administration to cover the incremental costs for low-embodied-carbon construction and surface road materials.[205] The Federal Highway Administration's Low Carbon Transportation Material program announced funding opportunities in late August 2024 for up to $1.2 billion for road construction materials, including cement, that have substantially lower GHG emissions than traditional materials.[206] This first round of funding is limited to state transportation departments, with the subsequent $800 million in funding to be made available to metropolitan planning and transportation agencies and local governments.[207] Federal funding cannot be used for projects that will result in additional through-travel lanes for single occupant passenger vehicles.[208] Eligible projects include reconstruction, rehabilitation, resurfacing, restoration, and preservation of existing lanes. To qualify, concrete must be in the 20th percentile of embodied carbon among similar materials (or a higher percentile if not available in the 20th percentile).[209,210] These emissions thresholds, while improvements, can largely be met through existing process efficiency and composition changes that reduce the amount of clinker or other substitutes. The Federal Highway Administration Low Carbon Transportation Material emission thresholds may not match those published by GSA for federal buildings, discussed in **Section 4.3** below.[211] This could present difficulties for federal contractors that procure and use cement for a range of federal building contracts, potentially increasing the administrative burden on contractors that wish to bid on different projects.

To support development of these low-carbon alternative materials, the Federal Highway Administration is collecting and plans to publish data on industry average embodied emissions for concrete and other materials.[212] The published data will help applicants determine the benchmark thresholds that low-carbon alternatives must meet. Importantly, the Low Carbon Transportation Material program allows funds to be used for training and technical assistance.[213,214]

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203 P.L. 117-169, § 60503.

204 P.L. 117-169, § 60504.

205 P.L. 117-169, § 60506.

206 U.S. Department of Transportation, Federal Highway Administration. n.d. *Low-Carbon Transportation Materials Grants Program.* Available at https://www.fhwa.dot.gov/lowcarbon/.

207 *Id.*

208 23 U.S.C. § 179 (b)(4)(C).

209 U.S. Department of Transportation, Federal Highway Administration. 2024. "Low-Carbon Transportation Materials Grants Program," *Frequently Asked Questions (FAQ).* Available at https://www.fhwa.dot.gov/lowcarbon/faq.cfm.

210 See also additional discussion below.

211 Personal email correspondence with Low Carbon Transportation Material Program Manager, Oct. 24, 2024.

212 U.S. Department of Transportation, Federal Highway Administration. 2024. "Low-Carbon Transportation Materials Grants Program", *Low Carbon Transportation Materials Grants Program Industry Averages.* Available at: https://www.fhwa.dot.gov/lowcarbon/industry_averages.cfm.

213 Training and technical assistance can include reviewing environmental product declarations, identification of embodied carbon thresholds, specification development, engineering materials testing, and placement costs for low-carbon materials during construction.

214 U.S. Department of Transportation, Federal Highway Administration, "Low-Carbon Transportation Materials Grants Program, Frequently Asked Questions (FAQ)." (Aug. 27, 2024). Available at https://www.fhwa.dot.gov/lowcarbon/faq.cfm.

Federal Funding for Research and Development

The United States delivers federal funding for R&D through programs administered by individual agencies. Agencies generally develop R&D budgets internally as part of the overall budget development process; agency proposals are then subject to review and revision by the Office of Management and Budget and ultimately by Congress as it completes the annual appropriations process.[215]

For cement decarbonization technologies, R&D funding primarily comes from DOE. For example, DOE provided $19 million in funding to five cement projects in October 2024, shown in **Table 11** below. DOE also provides funding to cement decarbonization projects through Advanced Research Projects Agency-Energy (ARPA-E), which advances high-potential, high-impact energy technologies that are too nascent or risky to attract private-sector investment.[216] ARPA-E recently announced a $14.5 million award to Queens Carbon to support the development and commercialization of its carbon neutral supplementary cementitious materials production,[217] and provided $498,254 in funding to Sublime from 2021–2023.[218]

DOE also provides support for demonstration projects through the Industrial Demonstrations Program. Finally, DOE sponsors R&D programs at the national labs. It recently announced it is making up to $9 million in IRA funding available to the national labs to bid on establishing a Cement and Concrete Center of Excellence to support collaboration across academia, the national labs, government agencies, and corporations to develop and validate novel low-carbon cement and concrete technologies.[219] One of the initial goals of the center is to develop improved tools and techniques for new binder chemistries.[220]

Table 11: Cement decarbonization projects awarded IEDO funding in October 2024

Project Name	Project Lead	Award Amount	State
Repurposing Dredged Sediment as an SCM for Producing Low Clinker Factor Cement & Concrete	Ash Grove Cement Company Inc.	$4,287,347	KS
Decarbonizing Concrete: Low-Temperature Calcined Clays as an Alternative Concrete Binder, Achieving Durability with Clay Beneficiation	Lehigh University	$2,000,000	PA
Advanced Electrolytic Cement Production Process for Lower-Energy Use with Alternative Calcium Sources	Sublime Systems	$6,690,175	MA
Value-added Mineralization of CO_2 from Cement Manufacturing in Recycled Concrete and Paste for Manufacturing of Low-carbon Cementitious Materials	CalPortland Company	$4,000,000	CA
Inter-grinding of Waste Activators and Low-grade Calcined Kaolin Clay for One-part Alkali-activated Concrete Technology	Princeton University	$2,000,000	NJ

Source: U.S. DOE. "IEDO Project Database." Available at: https://www.energy.gov/eere/iedo/iedo-project-database.

215 Congressional Research Service (CRS). 2023. *Federal Research and Development (R&D) Funding: FY2024.* Available at: https://crsreports.congress.gov/product/pdf/R/R47564.

216 ARPA-E. 2024. "About ARPA-E." Available at: https://arpa-e.energy.gov/about.

217 ARPA-E. 2024. "Queens Carbon." Available at: https://arpa-e.energy.gov/technologies/scaleup/scaleup-2023/queens-carbon.

218 ARPA-E. 2024. "Sublime Systems." Available at: https://arpa-e.energy.gov/technologies/projects/electrochemical-synthesis-low-carbon-cement.

219 U.S. Department of Energy. 2024. "U.S. Department of Energy Announces Plans to Create Low-Carbon Cement and Concrete Center of Excellence to Reduce Industrial Emissions." Available at: https://www.energy.gov/eere/iedo/articles/us-department-energy-announces-plans-create-low-carbon-cement-and-concrete.

220 Ibid.

4.3 Federal and State Procurement Efforts

As the world's largest purchaser, with an annual buying power exceeding $650 billion, the U.S. federal government wields substantial influence over its suppliers across domains.[221] The federal government accounts for roughly 25 percent of total spending on concrete in the United States.[222] In December 2021, President Biden leveraged this power by establishing the Federal Buy Clean Task Force and Initiative under Executive Order 14057.[223] This initiative aims to reduce embodied emissions in federal procurement and projects, while promoting clean, domestic manufacturing. The current focus is on sourcing low-carbon construction materials, particularly steel, concrete, asphalt, and glass—industries that together account for 98 percent of the federal government's material purchases.[224]

Since the issuance of Executive Order 14057, several federal agencies have begun implementing the Buy Clean initiative.[225] GSA, responsible for connecting federal purchasers with commercial products and services, introduced the first Buy Clean standards for concrete and asphalt in 2022, setting carbon limits on these products.[226,227] On May 16, 2023, the GSA also launched a six-month pilot program for the procurement of low-carbon materials, targeting 11 projects with the four key materials. For materials to be eligible under the $2.15 billion low-carbon construction materials program, they must satisfy GSA's embodied carbon requirements. In December 2023, GSA finalized its Low Embodied Carbon Concrete Requirements.[228] For cement, where practical, GSA will require that the material stay below the limits listed below, starting with cement in the Top 20 Percent Limit and moving on to the Top 40 Percent Limit or the Better than Average Limit only if material or product is available that meets these thresholds.[229]

- *Top 20% Limit:* 751 kilograms CO_2e per ton cement; in 2020, an estimated 25 cement plants met this target
- *Top 40% Limit:* 819 kilograms CO_2e per ton cement; an additional 14 cement plants (39 total) met this target in 2020
- *Better than Average Limit:* 858 kilograms CO_2e per ton cement; five additional plants (44 total) met this target[230]

These thresholds translate to materials that are about 13 percent less carbon-intensive, on a lifecycle basis, than traditional materials (assuming an average carbon intensity of 860 kilograms of CO_2e per metric ton cement).

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221 U.S. Council on Environmental Quality. 2023. "Federal Buy Clean Initiative." Available at: https://www.sustainability.gov/buyclean/.

222 Hasanbeigi, A., & Harshvardhan, K. 2021. *Scale of Government Procurement of Carbon-Intensive Materials in the U.S. Global Efficiency Intelligence*, at 23. Available at: https://www.globalefficiencyintel.com/scale-of-government-procurement-of-carbonintensive-materials-in-us.

223 The White House. 2021. "Executive Order on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability." Available at: https://www.whitehouse.gov/briefing-room/presidential-actions/2021/12/08/executive-order-on-catalyzing-clean-energy-industries-and-jobs-through-federal-sustainability/.

224 The White House. 2022. "Fact Sheet: Biden-Harris Administration Announces New Buy Clean Actions to Ensure American Manufacturing Leads in the 21st Century." Available at: https://www.whitehouse.gov/briefing-room/statements-releases/2022/09/15/fact-sheet-biden-harris-administration-announces-new-Buy Clean-actions-to-ensure-american-manufacturing-leads-in-the-21st-century/.

225 The White House. 2022. "Fact Sheet: Biden-Harris Administration Announces New Buy Clean Actions to Ensure American Manufacturing Leads in the 21st Century." Available at: https://www.whitehouse.gov/briefing-room/statements-releases/2022/09/15/fact-sheet-biden-harris-administration-announces-new-Buy Clean-actions-to-ensure-american-manufacturing-leads-in-the-21st-century/.

226 U.S. GSA. 2022. "GSA Administrator Highlights Progress on Low-Carbon Construction Material Procurement in Ohio." Available at: https://www.gsa.gov/about-us/newsroom/news-releases/gsa-administrator-highlights-progress-on-lowcarbon-construction-material-procurement-in-ohio-09152022.

227 U.S. GSA. 2022. "GSA Lightens the Environmental Footprint of its Building Materials." Available at: https://www.gsa.gov/about-us/newsroom/news-releases/gsa-lightens-the-environmental-footprint-of-its-building-materials-03302022

228 U.S. GSA. 2023. Inflation Reduction Act – Low Embodied Carbon Concrete Requirements. Available at: https://www.gsa.gov/system/files/Concrete%20-%20GSA%20IRA%20Low%20Embodied%20Carbon%20Requirements%20%28Dec.%202023%29_508.pdf.

229 Id. at 4.

230 Synapse Energy Economics. 2023. *Coming Clean on Industrial Emissions: Challenges, Inequities, and Opportunities in U.S. Steel, Aluminum, Cement, and Coke.* Prepared for Sierra Club. Available at: https://www.sierraclub.org/articles/2023/09/overview-coming-clean-industrial-emissions-report.

These thresholds signal to the private sector and federal government building contractors the emission limits their products must meet through certified EPDs to be considered for federal funding under the IRA.[231] The GSA recently announced $2 billion in funding for 150 projects across the United States, with an estimated $767 million to be spent on concrete, the largest product sector (followed by glass, steel, and asphalt).[232]

State procurement policies

State and local governments account for around 17 percent of total spending of concrete and cement products.[233] States, as the second-largest procurers of cement, play a pivotal role in driving demand for low-carbon alternatives. States receive both federal funding through formula grants and other types of funding and self-fund investments through state fuel taxes and other means.

In 2018, the top three largest purchasers of concrete for state transportation department projects were Texas ($1.2 billion), California ($1 billion), and Pennsylvania ($542 million); by total government-funded projects, Texas ($2.5 billion), California ($2.2 billion), and Pennsylvania ($1.1 billion) continue to lead.[234] The federal government provided $14 billion in grants to state transportation departments in 2024, positioning states and the federal government to influence the market for low-embodied-emission materials by (1) establishing performance-based standards, (2) setting achievable carbon emissions thresholds for materials, and (3) providing funding for cleaner alternatives.[235]

Performance-based material standards

Concrete specifications can vary by use case, with some uses dominating state or local markets. Due to its weight, cement is typically produced near its end-use location, so geographic differences in use cases or material inputs can result in different product compositions by geography. Typically, material standards for cement specify physical properties and related evaluation procedures, which can be either prescriptive or performance-based. Prescriptive specifications limit the composition of cement and its constituents by setting chemical or physical requirements that are indirectly tied to performance and by restricting the types of raw materials that can be used. By contrast, performance specifications focus solely on defining material performance requirements, such as compressive strength.[236] Two leading specification standards for cement—ASTM C 150 (for Portland cement) and ASTM C 595 (for blended hydraulic cement)—are prescriptive.

In 1992, the first performance-based specification for blended cements, ASTM C 1157, was issued. ASTM C 1157 establishes performance requirements with no specifications for the composition of the cement or its constituents. That standard has been revised and refined over the years. State transportation departments have traditionally developed state-specific prescriptive standards for construction materials, often based on national or third-party standards but customized to state requirements.[237] These state standards are typically then adopted by local governments for their own public works. Prescriptive standards are relatively easy to

231 P.L. 117-169, § 60503.

232 U.S. GSA. 2024. "Low-embodied carbon program detail." LEC program details. Available at: https://www.gsa.gov/real-estate/gsa-properties/inflation-reduction-act/lec-program-details.

233 Hasanbeigi, A., & Harshvardhan, K. (2021). "Scale of Government Procurement of Carbon-Intensive Materials in the U.S." *Global Efficiency Intelligence*, at 23. Available at: https://www.globalefficiencyintel.com/scale-of-government-procurement-of-carbonintensive-materials-in-us.

234 Hasanbeigi, A., & Harshvardhan, K. (2021). "Scale of Government Procurement of Carbon-Intensive Materials in the U.S." *Global Efficiency Intelligence,* at 25. Available at: https://www.globalefficiencyintel.com/scale-of-government-procurement-of-carbonintensive-materials-in-us.

235 U.S. Department of Transportation, Federal Transit Administration. 2024. "FY 2024 Full Year Apportionment State Totals." Available at: https://www.transit.dot.gov/funding/apportionments/fy-2024-full-year-apportionments-state-totals.

236 Concrete Construction. 1996. Prescriptive vs. Performance Cement Specifications. For a table comparing ASTM C 150, ASTM C 596, and ASTM C 1157 see https://www.concreteconstruction.net/_view-object?id=00000154-1cfa-db06-a1fe-7ffab4d40000.

237 See for example, Caltrans' Construction Details for Concrete, which list out acceptable concrete mixes for different use cases based on state adoption of national standards. CalTrans. 2019. "Construction Manual – Chapter 4: Construction Details, Section 90: Concrete." https://dot.ca.gov/-/media/dot-media/programs/construction/documents/policies-procedures-publications/construction-manual/sec4-90.pdf.

follow and implement, but reliance on a one-size-fits-all specifications creates a barrier to adoption of low-carbon cements, which may deviate from blend standards. A 2015 survey by the National Ready Mix Concrete Association of 102 project specifications found that 85 percent of projects' specifications limited the amount SCM that could be used, the most common type of prescriptive standard. Other prescriptive standards limit the amount of aggregate and water that can be mixed with the cement or require specific concrete densities per cubic centimeter.[238] Thirty states have at least one prescriptive-based concrete materials and composition standard with limited options for substitution of concrete with equal or better performance.[239] Such standards specify precise formulations, such as cement-type, clinker-to-water ratios, and aggregate requirements for specific project types. These prescriptive standards can inhibit market development and investment in lower-carbon alternatives by excluding innovative products from state procurement that may not meet the composition-based standards. An example is concrete with lower clinker ratios due to SCM substitution. To drive investment in low-carbon alternatives, states can transition to performance-based standards that focus on engineering properties—such as durability, compressive strength, tensile strength, and setting time. This allows contractors to procure blends from producers that meet these performance specifications.

By contrast, prescriptive standards may inhibit adoption of low-carbon concrete even when that concrete can meet the same performance criteria; for example, prescriptive standards often limit SCM to 25–50 percent by weight in concrete.240 Performance-based approaches, however, have shown that SCM use between 60–85 percent can achieve comparable durability with reduced emissions. Limestone calcined clay (LC3) cement, another promising clinker substitute, has up to 25 percent less production cost compared to Ordinary Portland Cement.[241] New LC3 production lines require some modification of existing clinker production lines, which literature suggests can be done with relatively low capital investment.[242,243,244] LC3 cement can reduce emissions by up to 40 percent and has a long history of performing as well as traditional Portland cement blends.[245] Moving toward performance-based standards can foster innovation within the cement industry enabling producers to lower costs and carbon emissions while maintaining safety and durability. The ready-mix industry is moving toward performance-based standards, at least for some types of cement and concrete, and some states have begun adopting performance-based standards. States are adopting performance-based standards for at least some types of end-uses. For example, a 2022 survey found that of 36 surveyed state transportation departments, 7 states' concrete specifications allowed performance-based specifications, specifically ASTM C 1157.[246] Several challenges face state transportation departments in adopting performance-based standards, including risk aversion and the need for workforce training to implement and verify new formulations. State transportation departments must ensure contractors are trained to meet and follow performance-based standards safely.[247] National standards bodies, such

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238 Obla, Karthik, and Labo, Colin. 2015. Prescriptive Specifications: A reality check. Concrete International. Available at: https://www.nrmca.org/wp-content/uploads/2020/09/prescriptive_specifications.pdf.

239 ClearPath. 2024. Paving the Way to Innovation: Moving from Prescriptive to Performance Specifications to Unlock Low-Carbon Cement, Concrete and Asphalt Innovations, at 11.

240 Id. at 13.

241 Hasanbeigi, A., Srinivasan, P., Chen, H., and Esram, N. 2024. "Adoption of Limestone Calcined Clay Cement and Concrete in the U.S. Market." *American Council for and Energy Efficient Economy,* at vii.

242 Kanagaraj, B., N. Anand, U. Alengaram, R. Raj, S. Karthick. 2024. Limestone calcined clay cement (LC3): A sustainable solution for mitigating environmental impact in the construction sector. Resources, Conservation & Recycling Advances 21, 2027, 200197. Available at: https://doi.org/10.1016/j.rcradv.2023.200197.

243 Diaz, Y., et al. 2017. Limestone calcined clay cement as a low-carbon solution to meet expanding cement demand in emerging economies. Development Engineering 2, 2017, 82-91 Available at: http://dx.doi.org/10.1016/j.deveng.2017.06.001.

244 LC3 Project. "About LC3" Available at: https://lc3.ch/about-lc3/. Accessed 1/2/2025.

245 Id. at ix.

246 *NCC Spring 2022 State Reports on Sustainability and Concrete Materials. 2022. National Concrete Consortium.* Available at: https://cdn-wordpress.webspec.cloud/intrans.iastate.edu/uploads/2022/04/05-Miller-State-Reports.pdf.

247 Hasanbeigi, A., Srinivasan, P., Chen, H., and Esram, N. 2024. "Adoption of Limestone Calcined Clay Cement and Concrete in the U.S. Market." *American Council for and Energy Efficient Economy,* at 15.

as ASTM, have recently adjusted specifications to incorporate more SCMs, but these standards remain prescriptive and require time to implement.[248] Notably, shipments of blended cement incorporating high levels of SCMs in 2023 are estimated to have increased fivefold over shipments in 2022 (to nearly one-quarter of all U.S. cement), so the standards may already be having a large effect[249] The National Ready Mixed Concrete Association is pushing for performance-based specifications to enhance quality, choice, and environmental benefits.[250] However, the multi-year process to update existing standards may be slowing adoption of new technologies. State transportation departments, contractors, and engineers may lack testing and modeling software and equipment to test and ensure that performance-based standards meet safety requirements for a particular project. Additional resources, such as a concrete-focused equipment loan program or increased funding for the Federal Highway Administration's mobile concrete technology center,[251] would support this transition by providing state transportation departments and contractors with the necessary testing and validation equipment.

Federal support for testing alternative cement formulations through national labs could further reassure states about adopting performance-based standards. For example, the Cement and Concrete Center of Excellence (discussed in **Section 4.2**) will bring together the research community and industry to develop new and improved tools and techniques; this includes approaches to testing and modeling cement performance, improving in-situ data collection and monitoring, and improving methodologies for calculating and reporting embodied and lifecycle emission to improve EPDs.[252] Collaborations with university research centers, such as the Rutgers University Center for Advanced Infrastructure and Transportation, could validate new materials, aiding states in setting informed and proven standards. The federal government could also encourage adoption of performance-based standards by adopting its own performance-based standards for federal projects and fund demonstration projects that rely on these updated standards. Finally, the federal government could condition state transportation departments' grant funding on the adoption of performance-based standards by state agencies.

State and local low-carbon standards

States and local governments can drive market demand for low-carbon cement alternatives by setting mandatory low-carbon standards for cement and concrete used in state contracts. Reliable third-party EPDs, discussed in detail in Section 4.1 above, are essential for this approach. States and local governments can start by first requiring contractors who bid on state construction contracts to post material EPDs in their bids.Currently five states require EPD submittals with state procurements for select construction materials. Local governments are also requiring increased transparency into the products they purchase. For instance, Portland, Oregon now requires concrete procurement proposals to include EPDs, establishing a maximum GHG threshold for new mixes.[253] New York City, Los Angeles, and Santa Monica all similarly have low-carbon and embodied carbon standards for construction materials.[254] Developing trustworthy EPDs can be a substantial cost for contractors, who tend to be smaller, local operators. States promulgating emission standards may need to provide workforce development and training to support widespread adoption and use of EPDs, but they may benefit from precedent established by EPA's work on EPDs.

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248 Hasanbeigi, A., Srinivasan, P., Chen, H., and Esram, N. 2024. "Adoption of Limestone Calcined Clay Cement and Concrete in the U.S. Market." American Council for and Energy Efficient Economy, at 15.

249 United States Geological Survey (USGS). 2024. "Cement 2022 tables-only release." Minerals Yearbook 2022, v. I, Metals and Minerals. Available at: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information.

250 National Ready Mixed Concrete Association. n.d. "Prescription to Performance (P2P) specifications frequently asked questions." P2P FAQ. Available at: https://www.nrmca.org/association-resources/research-and-engineering/p2p/p2p-faq/.

251 U.S. Department of Transportation, Federal Highway Administration. 2019. "Mobile Concrete Technology Center." Available at: https://www.fhwa.dot.gov/pavement/concrete/trailer/mission.cfm.

252 U.S. DOE. 2024. U.S. "Department of Energy Announces Plans to Create Low-Carbon Cement and Concrete Center of Excellence to Reduce Industrial Emissions. Industrial Efficiency & Decarbonization Office." Available at: https://www.energy.gov/eere/iedo/articles/us-department-energy-announces-plans-create-low-carbon-cement-and-concrete.

253 Natural Resources Defense Council (NRDC). 2022. *A Design Guide to State and Local Low-Carbon Concrete Procurement,* at 17. NRD No. R:22-04-A.

254 Haramati, Mikhail. 2024. State Strategies to Decarbonize Transportation Materials. DOT Clean Materials webinar. Available at: https://www.transportation.gov/sites/dot.gov/files/2024-10/National%20Resources%20Defense%20Council%20State%20Strategies.pdf.

States and local governments can then set ambitious but achievable thresholds for the maximum allowable amount of GHG emissions allowed in their procured cement and concrete as designated by their EPDs. Any product offered above that threshold would not be eligible for state contracts or states could choose to score a contractor that is using less-carbon-intensive products more favorably than those using cements or concretes above the threshold. This assumes that there is robust competition among contractors and available low-carbon cement to meet potential market demand. To be an effective market signal, states would have to give contractors a long lead time, likely several years, to procure low-carbon cement from producers. This requires producers to redirect investment, switch over production pathways, and develop verifiable EPDs. States could develop tiered thresholds as the federal government has done (see **Section 4.3**) to encourage a range of potentially lower-carbon alternatives. Furthermore, states can develop emission threshold ratchets that increase in stringency over time, with incentives for products that have lower embodied emissions than competitors. A ratchet would work by slowly but clearly setting out future required emission intensity reductions so as to send a strong market signal that products must continuously improve their emissions intensity over the years to remain eligible for state-funded projects. This would encourage contractors to compete with one another on multiple criteria rather than just on price.

State financial incentives and advanced purchase commitments

States can support lower-carbon cement by paying the cost differential between standard and low-carbon alternatives. State transportation grants and funding could offer financial incentives to cement products that meet emissions thresholds, with larger incentives for those with even lower emissions. Several states, including New York and New Jersey, offer "low-carbon bonuses" tied to emissions achievements in construction materials, making low-carbon options financially viable in state bids.[255] An approach similar to the federal government's commitment to advance-purchase agreements could be effective. By committing to substantial future purchases of low-carbon cement, states could further reduce market barriers and encourage suppliers to innovate in emissions reduction.

4.4 Federal Carbon Capture Storage and Utilization Tax Credits and Policy Support

CCUS technologies are expected to play a substantial role in industrial decarbonization. While there have been coordinated government efforts on further deployment of CCUS technologies, such as funding for several large-scale industrial CCUS hubs, adoption of CCUS remains slow. Thus, substantial uncertainty exists with respect to CCUS's overall contribution to cement decarbonization in the United States.

The IRA includes enhanced tax credits for CCUS projects on a per-ton-of-captured-CO_2 basis with higher credits for projects that permanently sequester the captured emissions.[256] The law increased the 45Q tax credit to as much as $85 per metric ton of captured CO_2 for 12 years after the CCUS equipment is placed in service. Prior to revisions to the tax credit in the IRA, a primary focus of CCUS investment focused on the electric power sector, while industrial emitters were eligible but at a higher emissions capture threshold. The IRA extended the life of the credit through 2032 and lowered the total capture threshold for eligible projects, qualifying smaller industrial sites.[257] The IRA made the tax credit technology-neutral and industrial emitters are eligible for the credit. Importantly, however, because the tax credit included an inflation adjustment mechanism beginning in 2027, its real value has diluted significantly due to elevated inflation that began in 2020. The value of the 45Q tax credit has already been devalued by about 6.5 percent since the IRA's passage in August 2022.[258]

Beyond federal tax credits, the federal government is working to finalize rules that could facilitate greater investment and deployment of CCUS technology. Currently, pipeline operators in the United States operate over 5,000 miles of CO_2 pipelines under robust federal and state oversight, though this network will require

255 Id. at 19.

256 P.L. 117-169, § 13104.

257 P.L. 117-169, § 13104.

258 Using the CPI Inflation Calculator, $85 in August 2022 (month of IRA signing) has the same buying power as $90.49 in September 2024. https://data.bls.gov/cgi-bin/cpicalc.pl?cost1=85&year1=202208&year2=202409.

significant expansion to meet projected CCS deployment needs. DOT's Pipeline and Hazardous Materials Safety Administration (PHMSA) regulates the operation of interstate CO_2 pipelines, and although PHMSA had announced a proposal to update CO_2 pipeline safety standard in January 2025,[259] no proposed rule has yet been published. The federal government has authority, under the *Safe Drinking Water Act*, over the approval of underground CO_2 injection wells through EPA's well class permitting system and the discretionary authority to grant this role to states under what is referred to as primacy.[260] Class VI primacy makes states responsible for processing applications for underground CO_2 injection, ensuring projects meet minimum federal requirements and any state regulatory requirement, as well as monitoring and enforcing safety standards. Currently, only three states have Class VI primacy (Louisiana, North Dakota, and Wyoming).[261] As of April 2024, West Virginia, Arizona, and Texas were in the pre-application phase for Class VI primacy.[262] Of the seven in-development cement-sector CCUS projects in the United States to date, only one project (the RTI International/Cemex plant in New Braunfels, Texas) is located in a state that has applied for Class VI primary.[263] For states without Class VI primacy, EPA is the primary regulator. As of December 2024, there are 166 Class VI well applications under review at EPA, with only four final permits issued so far. Many of these applications are in the technical review phase. There has been an uptick in applications, with one-third of all applications submitted in the last year, 79 applications submitted in 2023, and 35 submitted in 2024.[264] EPA has a goal of processing applications within 24 months of submittal. However, for applications submitted in 2021 and 2022 it is unlikely that EPA will meet this target due to delays ranging from 6 to 18 months.[265]

The IIJA appropriated $2.1 billion through 2026, under the DOE's Loan Program Office and the Office of Fossil Energy and Carbon Management, to stand up a Carbon Dioxide Transportation Infrastructure Finance and Innovation Program (CIFIA). The aim of the program is to support financing for large-scale shared CO_2 transport infrastructure.[266] The funding, through loan guarantees and federal credit instruments, supports common carriers such as pipeline owners and operators, rather than specific projects or developers of CCUS projects. The program aims to reduce lending risks and provide lower-cost capital to develop a network of CO_2 transportation assets, encourage partnerships with private CO_2 off-takers, and provide DOE's technical assistance. Eligible projects must cost more than $100 million and have a reasonable expectation of revenue through user fees or other revenue streams.[267] Loans would be capped at 80 percent of the reasonably anticipated eligible project costs.[268] The program requires that any funded project first receive all necessary federal environmental permits under the *National Environmental Policy Act* and that construction start within three months of receiving funding; this is a particularly challenging turnaround time given the other required permits.[269] DOE opened the funding opportunity announcement for the first tranche of $500 million in May 2024 but there have been no applications to date.[270]

259 https://www.phmsa.dot.gov/news/usdot-proposes-new-rule-strengthen-safety-requirements-carbon-dioxide-pipelines

260 42 U.S.C. 300h-1.

261 U.S. EPA. n.d. "Primary Enforcement Authority for the Underground Injection Control Program." *Underground Injection Control (UIC).* Available at: https://epa.gov/uic/primary-enforcement-authority-underground-injection-control-program-0.

262 Jones, A. Congressional Research Service. 2024. *Class VI Carbon Sequestration Wells: Permitting and State Program Primacy,* at 9-10. Available at: https://crsreports.congress.gov/product/pdf/R/R48033.

263 Clean Air Task Force. n.d. "U.S. carbon capture activity and project map." Available at: https://www.catf.us/ccsmapus/.

264 U.S. EPA. 2024. "Current Class VI Projects under Review at EPA, Class VI Permit Tracker Dashboard." Available at: https://www.epa.gov/uic/current-class-vi-projects-under-review-epa. (Last updated Dec. 6, 2024).

265 U.S. EPA. 2024. "Current Class VI Projects under Review at EPA." *Class VI Permit Tracker Dashboard.* Available at: https://www.epa.gov/uic/current-class-vi-projects-under-review-epa. (Last updated Dec. 6, 2024).

266 42 U.S.C. 16371.

267 42 U.S.C. 16373 (b)(3-4).

268 42 U.S.C. 16373(b)(2).

269 42 USC 16372(d)(2).

270 NETL. 2024. "DOE Announces up to $500 million to build a safe and reliable carbon dioxide transportation system." Available at: https://netl.doe.gov/node/13683.

4.5 Proposed Congressional Legislation

At the time of writing, Congress had recently introduced three coordinating pieces of bipartisan legislation that have the potential to further cement sector decarbonization technology development by supporting cross-sectoral RD&D for low-embodied emissions cement: the *Concrete and Asphalt Innovation Act*, or CAIA (S. 3439), the *Innovation Mitigation Partnerships for Asphalt and Concrete Technologies Act*, or *IMPACT Act* (H.R. 7685, H.R. 1534), and *IMPACT 2.0* (H.R. 9136). *IMPACT* and *IMPACT 2.0* are subsets of CAIA comprising the first and second half of CAIA, respectively.

The CAIA was introduced in the Senate in December 2023. This bill, which has yet to pass the Senate, would amend the *Energy Independence and Security Act* to support a low-emissions cement production research program.[271] This bill defines low-emissions cement and includes a list of technology pathways that can be used to meet emission reductions requirements.[272] Additionally, it would require DOE to establish a similar, cross-sectoral RD&D and commercial application program focusing on a list of enumerated technology decarbonization strategies, and it appropriates $200 million for a demonstration initiative.[273] Importantly, the bill also tasks DOE with creating and publishing baseline embodied GHG thresholds for cement that will signal to stakeholders and market participants how much less GHG-intensive their products must be in order to qualify as a low-emissions cement.[274] This component could be redundant or duplicative to the efforts being undertaken by EPA (see **Section 4.3**).

The CAIA further establishes a performance-based low-emissions materials grant program within the Federal Highway Administration.[275] This program would cover cost differentials for state transportation agencies between low-embodied emissions cement and traditional materials, alongside technical assistance and workforce training programs to update state codes and standards to be performance-based rather than content-based. The bill authorizes $15 million for this program through 2027, a relatively small total sum given the projected scale of demand for lower-carbon cements by states. The bill also supports an advance purchase commitment authority for the U.S. DOT to directly purchase or contract for low-embodied emissions cement.[276] Any advance commitment would have to be for the purchase of low-carbon alternative materials at least three years in the future from a private company, at a minimum quantity such that it meets performance standards. The program would allow DOT to explicitly give preference to low-carbon materials and processes that support decarbonization pathways over other materials. The lack of long-term off-take agreements between cement producers and the customers has been identified as a potential market hurdle to investing in decarbonization technologies,[277] and a federal advanced market commitment could alleviate some of that risk. However, the bill does not authorize any additional DOT funding to support the advance purchase commitment program. Finally, the bill establishes an interagency task force to further cement innovation, made up of DOE, DOT, Department of Defense, National Institute of Standards and Technology, and EPA.[278] The task force would consult with private sector stakeholders throughout the cement value chain, private companies, and code-setting and standards organizations. The task force would be tasked with developing performance-based rather than content-based standards for low-emission cement, establishing guidelines and best practices for testing and validation of new materials, and improving rules for EPDs for low-emitting materials.

The *IMPACT Act* (H.R. 7685), which roughly encompasses the first half of the *CAIA*, was introduced in March 2024 and was passed by the House in September 2024.[279] The bill was reintroduced in the 119th congress as H.R.

271 Concrete and Asphalt Innovation Act of 2023, S. 3439, § 3(a) (118th Congress).

272 S. 3439, § 3(b)(7) (118th Congress).

273 S. 3439, § 3(d)-(e), (g) (118th Congress).

274 S. 3439, § 3(i) (118th Congress).

275 S. 3439, § 5 (118th Congress).

276 S. 3439, § 6 (118th Congress).

277 U.S. Department of Energy. 2023. "Pathways to Commercial Liftoff: Low-Carbon Cement," at page 19. Available at: https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf.

278 S. 3439, § 7 (118th Congress).

279 Innovation Mitigation Partnerships for Asphalt and Concrete Technologies Act (IMPACT), H.R. 7685 (118th Congress). Would amend the IRA by including a new Sec. 40523 Advanced Cement, Concrete and Asphalt Production Research Program.

1534 in February, 2025, with minimal changes. The bill would amend the IRA with a new cement-materials-specific section, and aims to support advanced production pathways for cement that are, to the maximum extent practical, less GHG-intensive than commercially available cement.[280] In addition, it tasks DOE with establishing a coordinated research, development, demonstration, and commercial application program and strategic plan to facilitate research and leverage existing DOE national laboratory capabilities to achieve the commercialization of low-carbon cement.[281] The legislation focuses on a handful of technology pathways highlighted above, including CCUS, materials and process improvements, medium- and high-temperature low-carbon-intensive heat generation technologies, and materials efficiency improvements.[282] This bill is not just an R&D bill; it aims to support demonstrations of low-embodied-emission cements through projects with the DOT, GSA, industry, and university partners and national laboratories.[283] However, the legislation is vague as to the intended size or scope of the demonstration projects to be supported. Importantly, the bill also establishes a cross-agency technical assistance program to assist standards organizations in promoting the commercial application of lower-carbon cements, such as through collecting data to update local codes, conducting cradle-to-gate emissions analysis, testing procedures, and other technical requirements.[284] The bill does not authorize or appropriate any funds to carry out the legislative purpose of the bill, however. The third bill, *IMPACT 2.0*, was introduced in July 2024 and includes many of the market-supporting incentives found in the latter half of the CAIA.[285] To date, there has been no legislative movement on the *IMPACT 2.0* bill.

Carbon Advantage Legislation (Tariffs)

Because the United States is a dirtier producer of cement relative to the rest of the world there is a limited opportunity for so-called "carbon advantage" legislation to catalyze investment in domestically produced low-carbon cements. Carbon advantage legislation is premised on the idea that for industrial products for which the United States produces at a lower carbon intensity than importers, the United States can support domestic industrial investment and continue to reduce emissions by putting a carbon-based tariff on more carbon-intensive imports and investing those revenues into further decarbonization investments. The United States is a large importer of cement, but this cement is relatively less carbon-intensive than domestically produced cement, so any efforts to finance investment in decarbonization adoption strategies through a carbon tariff is unlikely to generate revenue at this time.

However, should these adoption strategies be successful in reducing U.S. cement industry carbon emissions relative to foreign nations, U.S. policymakers may consider implementing a carbon-based tariff on relatively more-carbon-intensive imports of cement to spur greater investment and domestic demand for low-embodied-carbon cement. Even if the United States is not a relatively lower-emitting producer of cement compared to importers, any carbon advantage legislation should include the cement sector because there would be relatively little cost to domestic producers, the U.S. exports relatively little cement so there is little risk of retaliatory tariffs on cement, and if and when U.S. cement becomes relatively less carbon-intensive then the carbon-based tariffs would be in place to capitalize on this carbon advantage of U.S. cement.

280 H.R. 7685, § 2(a)(7) (118th Congress).

281 H.R. 7685, § 2(b) (118th Congress).

282 H.R. 7685, § 2(e) (118th Congress).

283 H.R. 7685, § 2(f) (118th Congress).

284 H.R. 7685, § 2(g) (118th Congress).

285 H.R. 9136 (118th Congress).

4.6 Corporate Clean-Buyers Initiatives

A corporate clean-buyers association can take the form of a formal business association or an informal network of corporate purchasers committed to sourcing lower-carbon alternatives. These alternatives typically carry a higher initial cost than traditional options, especially in the early stages of market development. However, by leveraging their purchasing power and commitment, clean-buyers association members can signal to producers a willingness to pay a premium for lower-carbon products, thereby encouraging investment in these alternatives. Additionally, there are potential consumer marketing benefits to companies that signal that they are reducing their corporate emissions through new and innovative low-carbon technologies. A large, well-organized buyers collective could catalyze market growth for low-carbon cement alternatives, signaling strong corporate interest to developers and investors and helping to build demand for sustainable products.

Clean-buyers associations also create a platform for technical discussions between buyers and sellers, allowing purchasers to communicate their product needs and desired quality standards. One example is ConcreteZero, established in 2022. ConcreteZero comprises 40 global construction and design companies committed to procuring concrete that is 30 percent less carbon-intensive than the industry average by 2030.[286] Most ConcreteZero members are based in Europe or internationally, and U.S. participation remains limited. Of the 20 largest U.S. government building design and construction contractors, only two are ConcreteZero members, indicating an opportunity for greater domestic engagement in low-carbon procurement initiatives.[287]

4.7 Existing Clean Air Act Authority

EPA could consider using its existing authority under the *Clean Air Act* to accelerate the decarbonization of cement production. EPA could directly regulate GHG emissions from cement production when it revisits the Clean Air Act Section 111(b) New Source Performance Standards (NSPS) for cement manufacturing facilities.[288] NSPS apply to all listed categories of stationary sources, namely those that the Administrator has determined to "cause[], or contribute[] significantly to, air pollution which may reasonably be anticipated to endanger public health and welfare."[289] The NSPS for Portland cement currently regulate particulate matter, nitrogen oxide, and sulfur dioxide.[290] In addition to new facilities, NSPS provide the minimum stringency of controls for existing facilities that are major sources and undergo modifications, through the New Source Review program.[291]

EPA can use NSPS to regulate GHGs in addition to conventional air pollution such as particulate matter and ozone smog precursors. For example, EPA recently finalized standards for new gas power plants that specify different emissions limits for CO_2 emissions based on the Best System of Emissions Reduction (BSER) for three categories of electric generating units.[292] Indeed, EPA is obligated to set NSPS for GHGs for industrial categories with conventional air pollution NSPS, where it has information to support such a rulemaking, although there is no deadline for the development of such rules in the statute.[293]

EPA's development of such regulations, for both new sources under *Clean Air Act* Section 111(b) and existing sources under Section 111(d), would help ensure that all

286 ConcreteZero. n.d. "About ConcreteZero," *Climate Group Concrete Zero.* Available at: https://www.theclimategroup.org/concretezero.

287 Building Design and Construction. 2023. "Top 100 Government Building Construction firms for 2023." *Giants 400.* Available at: https://www.bdcnetwork.com/top-100-government-building-construction-firms-2023.

288 U.S. EPA. 2024. "Portland Cement Plants: New Source Performance Standards (NSPS)." Available at: https://www.epa.gov/stationary-sources-air-pollution/portland-cement-plants-new-source-performance-standards-nsps.

289 42 U.S.C. § 7411.

290 U.S. EPA. 2024. "Portland Cement Plants: New Source Performance Standards (NSPS)." Available at: https://www.epa.gov/stationary-sources-air-pollution/portland-cement-plants-new-source-performance-standards-nsps.

291 Lattanzio, R. Congressional Research Service (CRS). 2022. *Clean Air Act: A Summary of the Act and its Major Requirements,* at 13. Available at: https://crsreports.congress.gov/product/pdf/rl/rl30853.

292 U.S. EPA. 2024. "Final Carbon Pollution Standards to Reduce Greenhouse Gas Emissions from Power Plants." Available at: https://www.epa.gov/system/files/documents/2024-04/cps-presentation-final-rule-4-24-2024.pdf.

293 See, e.g., Portland Cement Ass'n v. EPA, 665 F.3d 177 (D.C. Cir. 2011) (rejecting ENGO attempts to require EPA to issue CO_2 performance standards for the Portland Cement industry when the conventional NSPS were last updated in 2010, because EPA asserted that it needed more information to do so).

new and existing cement plants invest in technology to reduce CO_2 emissions. This would drive the pace of emissions reductions from the cement industry and minimize investment in additional long-lived emitting assets. Additionally, once such standards are set, the statute requires that they be reviewed every eight years and revised as appropriate to reflect advances in pollution controls since the last round of standard setting.[294] So, while a particular technology may be adequately demonstrated to be the BSER supporting an emissions performance standard today (for new or existing sources), by 2032, a different technology may be adequately demonstrated to serve as BSER for more stringent standards. Additionally, EPA currently regulates hazardous air pollutant emissions from cement production facilities under the National Emission Standard for Hazardous Air Pollutants (NESHAP) program. The authority for NESHAP comes from Section 112 of the *Clean Air Act*. Under the program, EPA establishes standards for listed toxic air pollutants that are known or suspected to cause cancer or other serious health effects.[295] Both new and existing sources are regulated under the NESHAP program, and the emissions limits are based on the Maximum Achievable Control Technology (MACT) for the regulated air toxics emitted by sources in a listed industrial category. Stringent standards for hazardous air pollutants can have the co-benefit of also reducing other conventional air pollutants or GHGs, if the MACT is based on a lower emitting process that also results in CO_2 reductions. However, MACT for air toxics cannot be chosen on that basis.[296]

The current NESHAP standard for Portland cement manufacturing facilities covers particulate matter (as a proxy pollutant for air emissions of toxic metals), dioxins and furans, mercury, hydrocarbons, and hydrogen chloride emissions from new and existing kilns, clinker coolers, raw material dryers, and raw and finish mills.[297] EPA last amended the rule in 2018 when it finalized its Industry Residual Risk and Technology Review (RTR), the required periodic reassessment of NESHAP standards; it did not change the numerical emissions limits at that time.[298] EPA could update the existing cement NESHAP to reflect residual risks and technology improvements since 2013, when the numerical emissions limits were last revised.[299] A robust RTR analysis could yield not only public health benefits but potentially also co-benefit GHG emissions reductions, if any of the new standards could be met using inherently lower-carbon processes or inputs.

294 42 U.S.C. § 7411(b)(1)(B).

295 Lattanzio, R. Congressional Research Service (CRS). 2022. *Clean Air Act: A Summary of the Act and its Major Requirements,* at 11. Available at: https://crsreports.congress.gov/product/pdf/rl/rl30853.

296 See generally, 42 U.S.C. § 7412 (d)(3) (setting out the statutory factors for selecting new and existing source MACT).

297 40 CFR Part 63 Subpart LLL.

298 83 Fed. Reg. 35122.

299 78 Fed. Reg. 10006 (February 12, 2013).

SECTION 5

Policy Gap Analysis and Barriers to Implementation

This section identifies and evaluates missing or insufficient policies in the current cement decarbonization landscape, including direct financial support, market-based approaches, and regulatory actions. It concludes with cost estimates of near-term policy implementation and total capital investment needed through 2050 to decarbonize the U.S. cement sector.

5.1 Financial Support

Targeted support for low TRL technologies

Targeted research and development can help technologies currently at low TRLs advance to the point where they are ready for demonstration, eventual commercialization, and market take-off. This approach primarily involves federal funding for private companies and national and university materials labs to research technologies that are at early stages of development. Federal funding can help foster partnerships among academic, industry, and government researchers. To make use of this strategy, Congress would need to approve continued or expanded funding for DOE's industrial decarbonization initiatives, which DOE would then award to individual research projects, likely through its Industrial Efficiency and Decarbonization Office or ARPA-E. In the current federal policy context, states may have an important role to play to maintain support for cement decarbonization research and development; approaches could include research funding through state universities or direct development and deployment funding, such as North Carolina's One NC Small Business Program and the North Carolina Biotechnology Center.[300]

Gaps and barriers

While most decarbonization technologies could benefit from targeted research funding to some extent, the funding will have the most impact if DOE directs it toward technologies that have not received as much public support to date, such as bio-cement and alternative binder chemistries. Methods for retrofitting existing facilities to power kilns with alternative fuels or electrification could also benefit from additional targeted research.

The main barrier to policy implementation is the need to secure funding. DOE can fund some initiatives using money already appropriated to it, but obtaining new funding streams would require legislative action. Congress could appropriate additional funding to DOE through an independent piece of legislation, as it did when it provided funding for the Industrial Demonstrations Program in the IIJA. Congress could also appropriate funding during its annual budget process, in which case the money would flow through an existing DOE program.

Cost to implement

The size of federal and state awards for research and development varies by project. For the five cement decarbonization projects for which the Industrial Efficiency and Decarbonization Office recently awarded funding, the average award size was $3.8 million, with a minimum of $2 million and maximum of $6.7 million.[301] DOE could provide a similar level of funding to an additional five projects for a total cost of $19 million.

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300 North Carolina Department of Commerce. 2025. "Technology Funds" Available at: https://www.commerce.nc.gov/grants-incentives/technology-funds.

301 U.S. Department of Energy. 2024. "IEDO Project Database." Available at: https://www.energy.gov/eere/iedo/iedo-project-database.

Implementation risks

The abatement impact of this policy mechanism depends on adequate investment to develop new technologies to the point where they are ready for commercial deployment. Even with sufficient funding, not all early-stage technologies will ultimately succeed or be widely deployed. Even so, funding research and development for a broad array of technology options is beneficial because it preserves optionality; if one technology encounters challenges later in the commercialization process, there will be others available.

Impact

The direct abatement impact of this policy mechanism would initially be low, since it involves researching new technologies at a small scale. The emissions impact would grow over time as new technologies reach commercial readiness and start to be deployed more widely. Developing low TRL technologies provides foundational support to many of the other policy mechanisms, which depend on the availability of commercial-ready decarbonized cement technologies to succeed.

Pilot and demonstration project funding

Federal funding for pilot and demonstration projects supports technologies that are at a higher TRL and are ready for larger-scale demonstration. Federal funding can provide a cost-share with industry to construct pilots that bring down costs for future projects by advancing technologies from first-of-a-kind to nth-of-a-kind, unlocking learning curve benefits. While pilot funding for emerging technologies has historically been provided primarily by the federal government, states can create similar initiatives.

Gaps and barriers

Several cement decarbonization technologies could benefit from publicly funded pilot and demonstration projects. Methods for producing cement using alternative feedstocks and alternative production processes are gaining momentum, in part because of prior public support, and would benefit from additional funding for pilot and demonstration projects. In addition, the technologies discussed above that are currently at lower TRLs—including alternative binder chemistries, alternative fuels, and bio-cement—will benefit from pilot projects after advancing out of the research and development phase.

Similar to research and development, the main barrier to expanded support for pilot and demonstration projects is the need to obtain funding. Financial bankability is another key barrier, as emerging technologies could find it difficult to attract enough private sector capital due to their risk profiles. Increasing the amount of funding available to DOE to support pilot projects or funding state pilot initiatives would require legislative action.

Pilot and Demonstration Projects

Pilot and demonstration projects are different in the role each plays in technology development. A pilot project is typically a small, lab-scale test project that is used to test and evaluate the engineering and technology feasibility and effectiveness of a new technology or solution set (combination of new technologies working together). Using the TRL scale, a pilot is typically somewhere between TRL 3 *Critical Function or Proof of Concept* to TRL 6 *Prototype System*. A pilot is typically much smaller than what would be financially viable and is likely not suited to meet rigorous in-situ testing. Successful pilot projects provide critical data that allows developers to design more developed demonstration projects.

A demonstration project is typically defined as a larger-scale facility designed to showcase and validate technologies by deploying them in an operationally significant environment where the technology can be tested. A demonstration project is typically a first-of-a-kind project introduced at a lower range of commercially viability. A demonstration project is typically an order of magnitude larger than a pilot project and can allow for market testing and produce a commercially viable product for sale. Demonstration projects are much costlier and riskier than pilot projects but are critical for moving a pilot technology to market by demonstrating engineering, technical, and financial viability. Demonstration projects typically correspond to TRL 7 *Integrated Pilot System Demonstrated* to TRL 8 *System Incorporate into Commercial Design Applications*.

Derisking these pilot and demonstration projects through federal support could help mitigate concerns regarding financial bankability where emerging technologies find it difficult to attract private capital due to a project or technology's risk profile.

Cost to implement

In August 2024, the Industrial Demonstration Program announced that it had selected six cement demonstration projects to receive up to $1.6 billion in matching federal investment.[302] The individual awards range from $62 million to $500 million, with an average size of $259 million. Cost-sharing with industry reduces the amount of federal funding required per project, although these awards are still significantly larger than the R&D awards from DOE. Pilot project funding would likely fall in a lower cost range, with each pilot project grant being several million dollars. For example, ARPA-E provided Sublime Systems with a $7 million, 50/50 cost share, grant to support a pilot project.[303]

Implementation risks

A primary goal of pilot projects is usually to reduce costs for future projects by gaining experience constructing the technology at larger than bench-scale. One common metric for quantifying the learning-related cost reductions available to a given technology is its learning rate, which is the percent reduction in project costs associated with each doubling of installed capacity.[304] Depending on the technology, a risk of funding pilot projects is that the pilots may not yield hoped-for cost reductions. Because allocating large amounts of funding to pilot projects has an opportunity cost, it is important to be realistic about the cost savings available to a given technology.

Figure 10 shows one framework for understanding why certain technologies have higher learning rates than others. Type 1 technologies, which have a low degree of complexity and low need for customization such as solar PV modules, tend to have the highest learning rates. Type 3 technologies, which have high complexity and/or high requirements for customization, have less potential for learning-curve savings. Some Type 3 technologies, such as conventional nuclear power plants, may even experience cost increases associated with increased installed capacity.[305]

Notably, CCUS falls into Type 3, since the technology is highly complex and requires a moderate level of customization (both at the facility level and between the different sectors where CCUS could be applied). **Table 12** summarizes the CCUS learning rates identified by eight recent studies covering a variety of sectors; values range from 2 to 14 percent, with an average value of 7 percent. In contrast, solar PV modules, which are Type 1, have an average learning rate of 21 percent, three times higher than CCUS. This suggests that CCUS pilot projects are likely to yield only moderate cost savings. Other cement decarbonization technologies may have larger potential cost declines. For example, electrochemical production is likely a Type 1 technology, since it is inherently modular due to the wide availability of industrial-sized acid/base electrolyzers from the specialty chemicals and burgeoning hydrogen industry.[306] Several other technologies, including electric kilns, alternative feedstock processes, and alternative binder chemistries, will likely require a moderate amount of customization and will fall under Type 2.

Impact

As with targeted support for low TRL technologies, the direct GHG abatement impact of pilot projects will be small at first but will enable future emissions reductions. Each pilot project will reduce emissions in proportion to the amount of traditional cement it replaces with low- or zero-carbon cement. For example, one of the recipients of IDP funding, Sublime Systems, plans to use the funding to contribute a 30,000 ton per year production facility in Holyoke, Massachusetts.[307]

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302 U.S. DOE. 2024. "Industrial Demonstrations Program Selected and Awarded Projects: Cement and Concrete." Available at https://www.energy.gov/oced/industrial-demonstrations-program-selected-and-awarded-projects-cement-and-concrete.

303 U.S. DOE. ARPA-E. 2022. "Sublime Systems". Available at: https://arpa-e.energy.gov/programs-and-initiatives/search-all-projects/electrochemical-upcycling-low-co2-materials-production.electrochemical-upcycling-low-co2-materials-production.

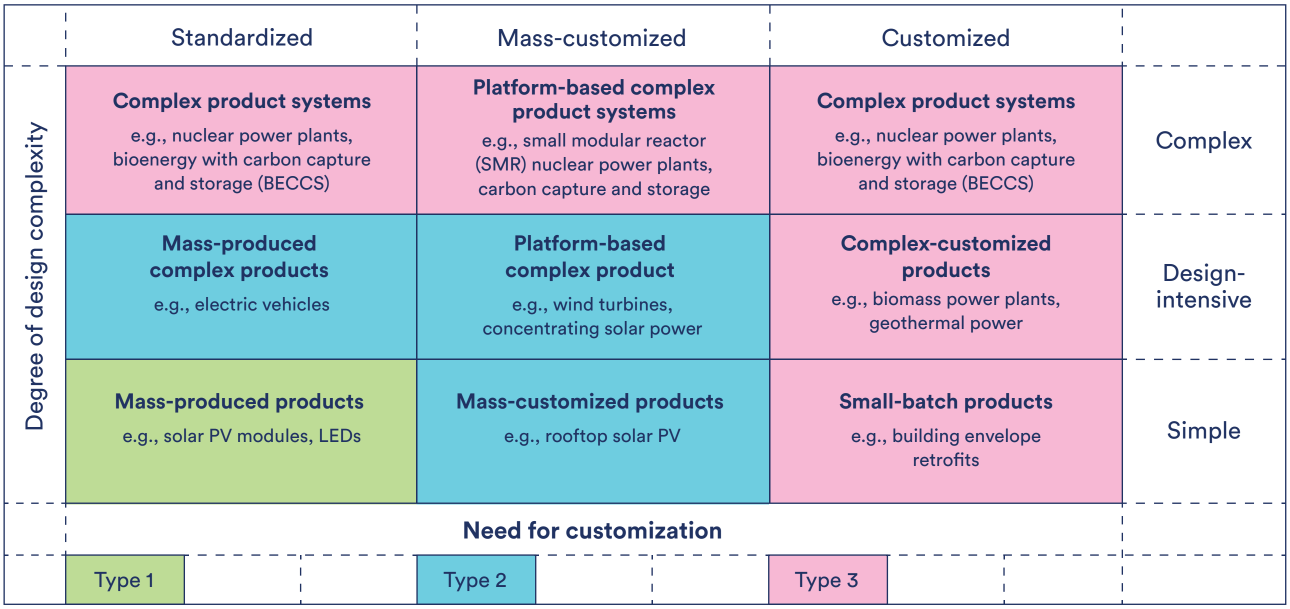
304 Eash-Gates, P, Klemun, M, Kavlak, G, McNerney, J, Buongiorno, J, and Trancik, J. 2020. Sources of Cost Overrun in Nuclear Power Plant Construction Call for a New Approach to Engineering Design. Joule 4, 2348–2373. Available at: https://doi.org/10.1016/j.joule.2020.10.001.

305 Id.

306 International Energy Agency. 2023. "Electrolysers." Available at: https://www.iea.org/energy-system/low-emission-fuels/electrolysers.

307 Winn, Z. 2024. "With sustainable cement, startup aims to eliminate gigatons of CO_2." MIT News. Available at: https://news.mit.edu/2024/sustainable-cement-startup-sublime-eliminates-co2-gigatons-0809.

Figure 10: Framework for understanding potential of low-carbon technologies for learning-based cost savings



Adapted from: Malhotra, A and Schmidt, T. 2020. Accelerating Low-Carbon Innovation. Joule 4, 2259–2267. Available at: https://doi.org/10.1016/j.joule.2020.09.004.

Table 12: CCUS experience rate estimate from eight studies of project costs

Geographic scope	Experience rate estimate
Global	2%
Global	2%
Global	3%
Global	5%
China	8%
China	14%
U.S., Germany, & Japan	12%
Global	13%

Source: Malhotra, A and Schmidt, T. 2020. Accelerating Low-Carbon Innovation: Supplementary Information. Joule 4, 2259–2267. Available at: https://doi.org/10.1016/j.joule.2020.09.004.

Current U.S. cement production has an average emissions intensity of 0.83 tons of CO_2e per ton of cement, so this pilot will avoid approximately 25 kilotons of CO_2e per year, assuming that all of the cement it produces displaces traditional cement.[308] Pilot funding can have a large, secondary impact by initiating learning curve cost reductions that enable widespread adoption if a technology becomes cost-competitive.

Policy and regulatory support for CCUS deployment

CCUS adoption for cement plants remains at a relatively early stage, with a handful of commercial demonstration projects slated to begin construction and procurement in the next few years, including two projects in the United States and six in Europe (see **Section 3.4**). Accelerating the commercialization and deployment of CCUS in the U.S. cement sector will require additional policy support, as we discuss in more detail below.

Gaps and barriers

Ongoing CCUS pilot and demonstration projects, including those announced as part of the Industrial Demonstrations Program and additional projects in Europe and Australia, will help demonstrate the feasibility of this technology on cement plants. Due to the complexity of CCUS equipment, available cost savings from pilot projects are likely to be limited (between 2 and 14 percent for every doubling of installed capacity; see above). Given that there will likely continue to be a cost premium for cement produced with CCUS, establishing incentives that make CCUS cost-effective on cement plants will be key to wider deployment of this technology. The most likely mechanism for achieving CCUS cost-effectiveness is an expanded 45Q tax credit. The 45Q tax credit currently provides up to $85 per metric ton of captured CO_2 for 12 years after CCUS equipment is placed in service, if the CO_2 is permanently sequestered. This value is generally too low to incentivize CCUS at cement plants.

If the captured CO_2 is utilized in other industrial processes, then the credit value is $60 per ton (although there is presumably some economic value to account for the value of the utilized CO_2). DOE estimates that the cost of post-combustion CCUS is between $35–75 per metric ton of CO_2 higher than the $85 per metric ton 45Q tax credit (equivalent to $25–55 per ton of cement).[309] Expanding the 45Q tax credit would require legislation and could have a high policy cost if uptake of CCUS is high. Tailoring the increased tax credit to specific sectors such as cement production that have high costs to install CCUS would help limit the increase in policy cost.

In addition to making CCUS cost-competitive, another key element to enabling its adoption is removing ecosystem barriers related to CO_2 infrastructure and storage availability. Deployment of CCUS on cement plants and other industrial facilities depends on the availability of infrastructure to transport and store captured CO_2. CIFIA, established by the IIJA, was intended to offer loans and loan guarantees for CO_2 pipeline construction, but developers have been unwilling to apply for the funding. This is largely because of the associated NEPA requirements and the requirement that construction must begin within three months of receiving funding. Streamlining CIFIA requirements would allow developers to access the funding and would help accelerate CO_2 infrastructure buildout. In addition, streamlining the process for EPA's Class VI well permitting would further facilitate buildout of the necessary CO_2 infrastructure.

Cost to implement

The cost of policy and regulatory support for CCUS varies by policy mechanism. On the lower end, OCED recently awarded up to $500 million to each of two cement companies to build commercial-scale carbon capture units at existing cement plants in Indiana and California.[310]

The 45Q tax credit has a much higher policy cost, because it involves ongoing payments to CCUS projects. The Treasury Department reports that companies claimed about $1 billion in Section 45Q tax credits from tax years 2010 to 2019, before the IRA increased

308 (30,000 tons of cement/year)*(0.83 tons CO_2e/ton cement) = 24,900 tons CO_2e/year. This calculation assumes that the Sublime plant will have zero Scope 1 or 2 emissions. The plant will primarily be powered with hydroelectricity from the municipal utility in Holyoke.

309 U.S. Department of Energy. 2023. "Pathways to Commercial Liftoff: Low-Carbon Cement" Available at: https://liftoff.energy.gov/wp-content/uploads/2023/09/20230918-Pathways-to-Commercial-Liftoff-Cement.pdf.

310 U.S. DOE. 2024. "Industrial Demonstrations Program Selected and Awarded Projects: Cement and Concrete." Available at https://www.energy.gov/oced/industrial-demonstrations-program-selected-and-awarded-projects-cement-and-concrete.

credit value and eligibility.[311] Cost estimates for the IRA's expanded 45Q credit vary widely, because they depend on projections of future technology uptake. The Joint Committee on Taxation projects that the expanded tax credit will cost the government about $5 billion from 2023–2027.[312] Other estimates are more optimistic about buildout of CCUS and project costs ranging from $30 billion to $100 billion for the IRA-expanded credit.[313] If the 20 U.S. plants with the largest annual cement production installed CCUS equipment that captured 95 percent of their Scope 1 CO_2 emissions, annual federal expenditure on 45Q payments would be $3.2 billion per year at the current credit level of $85 per metric tons of CO_2 (**Table 13**). If Congress increased the value of the credit to $140 dollars per ton of CO_2, federal expenditures would increase to $5.3 billion per year for the top 20 facilities. This amount of CCUS uptake would eliminate 37.7 million metric tons of CO_2 per year, which is equivalent to 56 percent of sector-wide Scope 1 emissions.

If all U.S. cement plants installed CCUS, annual federal expenditures on tax credits would be $5.4 billion at the current credit level, or $8.9 billion if the credit was increased to $140 per ton of CO_2. Emissions reductions in this scenario would be 63.4 million metric tons of CO_2 per year (assuming a 95 percent capture rate). In reality, the deployment of CCUS will be limited by the economic and technical feasibility and by the availability of carbon transport and storage infrastructure, so this represents an upper bound on the cost and mitigation potential of this approach.

To support CO_2 infrastructure buildout, IIJA provided $2.1 billion in advance appropriations for the CIFIA program.[314] This money has not yet been used, so it is still available for use supporting CO_2 pipeline buildout.

Implementation risks

The abatement impact of policy support for CCUS will be low if tax credits are not increased to the point where CCUS is cost-effective, if CCUS remains at a low TRL, or if CCUS projects are unable to secure financing. Cement produced with CCUS will likely continue to have a price premium due to the complexity of CCUS technology, so deployment of CCUS will depend on the continuous availability of tax credits or other policy approaches. In addition, the effectiveness of an expanded 45Q credit is contingent on sufficient buildout of CO_2 transportation and storage infrastructure. Difficulty accessing financing

Table 13. Annual federal policy cost of expanded 45Q tax credit at two illustrative levels of CCUS deployment

Cement Plants Installing CCUS	Annual Cement Production (MMT cement/year)	Scope 1 CO_2 Emissions (MMT CO_2/year)	Emissions eliminated with 95% carbon capture (MMT CO_2/year)	Annual Federal Expenditure with $85/ton Credit (Billion $/year)	Annual Federal Expenditure with $140/ton Credit (Billion $/year)
20 highest producing cement plants	50.4	39.7	37.7	$3.2	$5.3
All U.S. cement plants	85.5	66.8	63.4	$5.4	$8.9

Source: Synapse Energy Economics. (2023). Coming Clean on Industrial Emissions: Challenges, Inequities, and Opportunities in U.S. Steel, Aluminum, Cement, and Coke. Prepared for Sierra Club. Assumes that CCUS operates with 95 percent capture rate.

311 Congressional Budget Office. 2023. *Carbon Capture and Storage in the United States.* Available at: https://www.cbo.gov/publication/59832.

312 Ibid.

313 Ibid.

314 Congressional Research Service. 2024. *DOE's Carbon Capture and Storage (CCS) and Carbon Removal Programs.* Available at: https://crsreports.congress.gov/product/pdf/IF/IF11861#:~:text=IIJA%20provided%20%242.1%20billion%20for,which%20was%20provided%20for%20FY2023.

could slow this process, as could community opposition to CO_2 infrastructure siting. Community concerns generally center around safety and environmental protection issues, including impacts on air quality and groundwater quality, protection in the event of leakage or well failure, and the impact on mineral rights and property values.[315] Working with communities to adequately address these concerns will be key to successful infrastructure buildout.

Impact

Policy and regulatory support for CCUS deployment has high potential mitigation impact. As discussed above, 95 percent carbon capture equipment installed on the 20 largest U.S. cement plants would eliminate 37.7 million metric tons of CO_2 per year, equivalent to 56 percent of sector-wide Scope 1 emissions.

5.2 Market-Based Approaches

Transparent and verifiable third-party labeling

Environmental product labeling and EPDs play a vital role in fostering a market for low-carbon products, including cement. EPDs should be product-specific, user-friendly, and based on transparent, verifiable data validated by independent third-party verifiers. EPDs are primarily designed for business-to-business communication rather than public use and there is already a robust process for setting up and verifying product-specific EPDs in the United States. EPDs are likely to be especially crucial and impactful for cement products due to the diversity of cement types and sources and the need to ensure comparison of like-to-like products. EPDs have been around for more than three decades, with their use beginning in Europe and spreading to the United States.

A product- and plant-specific cement EPD serves as a straightforward label for a product shipment, detailing the cradle-to-gate emissions associated with that specific product. As Type III environmental declarations, EPDs adhere to the principles of ISO 14025 and 21930. With a well-established history in the construction materials sector, EPDs benefit from a growing array of technologies and companies dedicated to their development and third-party verification to ensure accuracy and reliability.

Gaps and barriers

EPDs only measure emissions along the supply chain through production, rather than life-cycle emissions. A cement product that has lower life-cycle emissions but similar cradle-to-gate emissions will be at a comparative disadvantage from an EPD perspective to a cement with higher life-cycle emissions. Additionally, to provide the most accurate information, EPDs must be product- and end-use specific, making comparing different types of cement across different end uses difficult (for example, earthquake-grade building cement in California compared to highway cement in New York). Finally, industry comfort and familiarity with EPDs remains a barrier to adoption despite their long history, although the U.S. cement industry leads all other U.S. industries in EPD adoption. Given necessary technical expertise required to produce a product-specific EPD, workforce training and technical assistance is necessary for developing an understanding of the information conveyed in an EPD.

Cost to implement

The primary costs to implement an EPD is the cost of the relevant equipment and know-how necessary to produce high-quality verifiable EPDs alongside third-party certification. While new automated tools and the use of blockchain technology is being developed to facilitate EPD development, the cost to develop EPD can be significant. An international study found that the total cost to develop an EPD ranged from $13,000 to $41,000 per product and required between 22 to 44 employee-days.[316] This could represent a substantial staffing and budget concern for smaller cement firms. This is particularly problematic for firms that produce many different types of cement products, which would each require unique labels. State and federal support in the form of tax credits, grants, or technical assistance could reduce these costs.

Implementation risks

The primary implementation risk for EPDs for cement products is if they are not transparent or accurate as to the actual cradle-to-gate emission associated with the product, it will reduce buyer confidence in the associated products and EPDs more broadly.

315 Jones, A. 2022. *Injection and Geologic Sequestration of Carbon Dioxide: Federal Role and Issues for Congress.* Congressional Research Service. Available at: https://crsreports.congress.gov/product/pdf/R/R46192.

316 Tasaki, Tomohiro & Shobatake, Koichi & Nakajima, Kenichi & Dalhammar, Carl. (2017). *International Survey of the Costs of Assessment for Environmental Product Declarations.* Procedia CIRP.

Market confidence in EPDs is critical, given that other policy adoption strategies such as government procurement standards and contracts for difference (CfDs), described below, rely on product emission ratings to validate lower-carbon purchases. Without trustworthy EPDs, buyers may be unwilling to pay a premium for a product due to uncertainty in environmental benefits.

Impact

While labeling itself does not directly reduce emissions, verifiable EPDs are foundational to a robust market for lower-carbon cement and are key to supporting other adoption strategies with high abatement potential. As noted above, state low-carbon cement procurement programs rely on verifiable, product-specific EPDs, indicating that buyers already view them as key to facilitating a low-carbon cement market. EPDs will facilitate the market for low-carbon cements by providing purchasers with a clear indication of which products are lower carbon, allowing low-carbon cement producers to earn a premium over traditional cement.

Advance market commitments

An Advanced Market Commitment (AMC) is a demand-pull strategy that establishes a minimum price or volume guarantee for specific products that a government or private entity plans to purchase in the future. An AMC is a guarantee to purchase the product at a future date, contingent on product availability at specified quantities and price. This approach incentivizes producers by ensuring a reliable buyer for their product and signals a willingness to pay that is above the market price absent an AMC. An AMC works by sending a strong and immediate signal that there is a market for a product. Strengths of this strategy include avoiding specifying winning technologies, maintaining optionality, and derisking investment in emerging technologies. AMCs can drive innovation for technologies at various stages of development and commercialization. For technologies close to commercialization, AMCs primarily serve to demonstrate market demand, encouraging investments in production capacity. For more distant technologies, AMCs aim to foster early-stage research, development, and deployment, which can expand optionality. AMCs have been particularly successful in vaccine development and advancing atmospheric CO_2 removal.[317,318] As another example, OCED launched a $1 billion program to promote clean hydrogen development through market-based strategies, including AMCs with specified price and volume requirements.[319]

A hypothetical example AMC development in the cement sector would be a coalition of major technology companies committing to purchase 10 million tons of verifiable low-carbon cement by 2028 at an above-market price per ton. Alternatively, they might announce a $1 billion fund to buy low-carbon cement at a maximum price per ton, signaling to producers robust market demand. While individual companies such as Amazon and Microsoft have pledged to use low-carbon construction materials, a coordinated industry-wide effort has yet to emerge. Some states are taking the lead in signaling demand for low-carbon cement. For example, a proposed 2023 California bill would mandate that at least 10 percent of publicly procured cement meet low-carbon standards by 2035.[320] Several states could pool their public procurement funding to increase the total amount of low-carbon cement desired by a certain future date.

Gaps and barriers

Currently, there is no federal minimum price or volume guarantee for low-carbon cement. OCED issued a request for information on leveraging demand-side support for clean technologies, including cement.[321] However, no formal AMC for low-carbon cement to meet federal demand has been announced to date. Despite lack of federal action, in early 2024, the First Movers Coalition—comprising large multinational companies—announced a commitment to low-carbon cement and concrete, specifying thresholds for strength and embodied carbon;[322] to date, however, the coalition has not organized a U.S.-based AMC. Cement procurement

317 Center for Global Development, Making Markets for Development Innovations.

318 See Frontier, an AMC for direct air capture that is funded at $1 billion by major technology firms. Available at: https://frontierclimate.com/.

319 DE-NOI-0202301: Bipartisan Infrastructure Law: Additional Clean Hydrogen Programs (Section 40313): Regional Clean Hydrogen Hubs.

320 California Senate Bill 682. 2023. Available at: https://legiscan.com/CA/text/SB682/id/2794100.

321 U.S. DOE, OCED. 2023. "Public Insight Requested for Demand-Side Support for Clean Energy Technologies." Available at: https://www.energy.gov/oced/articles/public-insight-requested-demand-side-support-clean-energy-technologies.

322 World Economic Forum. 2024. Cement and Concrete First Movers Coalition. Available at: https://www3.weforum.org/docs/WEF_FMC_Cement_Concrete_Commitment.pdf

typically involves job-specific contracts negotiated close to project completion. AMCs would require a shift toward longer negotiation horizons to enable producers to meet embodied carbon standards with new technology investments, which would require changes to traditional procurement protocols. Additionally, the cement industry's regionalized nature, driven by high freight costs, presents challenges for establishing a national-level AMC. Another barrier is determining an appropriate price or output level that incentivizes producers to make significant, capital-intensive investments in emissions-reducing technologies. Prices must be generous enough to drive market transformation, yet affordable to encourage widespread participation.

Cost to implement

An AMC can be structured as a voluntary public-private partnership involving producers and federal or state governments. Alternatively, large private cement consumers could establish a cement or building materials AMC. Participants could collectively set targets, such as a group-wide goal, a minimum price, or a total funding commitment. Upfront costs for implementing an AMC would be minimal. The process would involve convening stakeholders, defining the desired minimum price or quantity of low-carbon cement, and establishing timelines. Material performance-based standards would likely be necessary to meet builders' specific needs while incentivizing new and innovative technologies. Instead of requiring significant upfront funding, an AMC could issue binding letters of intent to provide certainty to producers and only make purchases once the product is available.

For a government-led AMC, funding would likely need to be pre-appropriated and earmarked for future low-carbon cement purchases. Implementation costs would include holding these public funds and administering the program. Administrative tasks would involve informing market suppliers about the AMC and its requirements, regularly updating the commitment to align with technological advancements, and verifying that purchased products meet the specified performance and embodied carbon emission standards.

Implementation risks

The main implementation risk of an AMC lies in the potential failure of the market to supply low-carbon cement within the timeframe required by purchasers. Additionally, high freight costs constrain the locations where AMCs are likely to be effective. While the AMC should be technology-neutral, reducing the risk of technological failure would require encouraging participation from a diverse range of providers using different technologies. Effective evaluation, monitoring, and verification are also critical; failure in these areas could compromise purchaser confidence by raising doubts about whether the delivered cement meets low-carbon standards.

Impact

An AMC has the potential to have a medium-to-large abatement potential by supporting commercialization of innovative technologies and processes. Signaling to the market that there is a large pool of interested buyers of low-carbon cement could jumpstart investor interest, bringing in much-needed capital. By being technology-neutral and performance-based, an AMC couldencourage multiple technological approaches. The direct air capture AMC, Frontier, has contracted close to $350 million for 635,000 tons of CO_2 removal since 2023.[323] A similarly ambitious cement AMC with commitments of $1 billion could fund 5 million tons of low-carbon cement production, even at 25 percent premium above current cement prices. Importantly, there would be additional capital expenditures required by producers to produce lower-carbon cement, but an AMC would signal a financial appetite to pay a premium for a lower-carbon product.[324] Assuming AMC-purchased cement was 25 percent less carbon intensive than traditional cement with a carbon intensity of 0.83 MT/ton (see **Table 3**), the carbon emissions savings would be approximately 1 million metric tons, or about $1,000 per ton of carbon abatement.[325]

323 Frontier. 2024. Progress. Available at: https://frontierclimate.com/progress.

324 2024 cement prices averaged around $157 per ton. A $1 billion AMC would be able to purchase roughly 5 million tons of low-carbon cement at a 25 percent premium above current cement prices. *See* IBISWorld, Business Environment Profiles – United States, Price of Cement. (Aug. 22, 2024).

325 Assuming that the 5 million tons of cement is purchased through the AMC is 25 less carbon intensive implies a carbon intensity of 0.623 metric tons CO_2 per ton. The difference in total emissions is roughly 1 million metric tons.

Clean cement buyers association

A clean cement buyers association differs from an advanced market commitment by representing large cement procurers such as building contractors or engineering, procurement, construction firms (EPC) rather than end-use consumers such as federal and state governments and large private companies like Amazon or Google. A buyers association is also more focused on near-term contracts for products whereas an AMC is intended to send long-term market signals. While an AMC is a promise to purchase a product that meets desired specifications, a buyers' association is an organized group of purchasers who can signal to the market that there is substantial demand for a lower-carbon alternative. A clean cement buyers association would likely be made up of large building firms that contract with federal, state, and private companies to build projects such as highways, ports, data centers, and other cement-intensive construction. A clean buyers association would work by setting baseline emissions intensity standards alongside ambitious but achievable near-term targets.

Gaps and barriers

The Concrete Zero initiative organized by the Climate Group is a predominantly European-based buyers' club, with no comparable U.S. equivalent.[326] A U.S.-based buyers association would include large domestic building and contracting companies, such as AECOM, Bechtel, Fluor, and Clark Group, to name a few. Barriers to implementation are primarily administrative and include establishing and organizing a collaborative among firms who may be direct competitors. Once established, another hurdle is establishing carbon intensity baselines, reduction targets, and purchase quantities that the association could collectively agree upon.

Cost to implement

The cost to implement a private-sector U.S.-based clean buyer association is likely minimal. Major U.S. construction firms could decide to join ConcreteZero or form their own domestic organization. Firms could rely on environmental non-profits and similar organizations with expertise in organizing buyers' commitments.

Implementation risks

The main implementation risk for a clean cement or concrete buyers' association lies in firms committing to carbon emissions reduction targets without the availability of low-carbon cement products or technologies to achieve those goals in the near term. Additional risks include setting standards that are either too ambitious for the market to meet or too lenient, which would fail to meaningfully challenge the market to drive new investment. While price premiums for low-carbon cement alternatives could pose a risk, these costs are unlikely to significantly impact the overall expenses of large construction projects, as cement typically represents only a portion of the total budget. A private buyers association, organized as a group purchasing entity, could raise concerns about violating federal or state antitrust monopsony laws if the purchasing commitment is large enough to distort the market. However, since a clean buyers group typically involves paying a premium for low-carbon cement and aims to promote rather than suppress competition, significant antitrust risks are unlikely.[327]

Impact

As large purchasers of cement products, U.S. construction firms that serve both private and government building contract needs could send a strong market signal to start-ups and providers of low-carbon cement technology alternatives. Similar to an AMC, a $1 billion buyers commitment to purchase low-carbon cement would likely drive billions in investment and, if successful, incentivize production of low-carbon cement at a cost that does not substantially impact overall construction costs for the average project.

Government procurement models

Government procurement of low-carbon cement can capitalize on the significant influence federal and state governments wield within the cement industry as the first and second largest purchasers, respectively. The federal government has unique power to derisk low-carbon cement investments and reward first movers.

[326] See Climate Group -Concrete Zero "About ConcreteZero". Available at: https://www.theclimategroup.org/concretezero-members.

[327] Mayer Brown. GPOs – *Not just for Healthcare Industry.* Available at: https://www.mayerbrown.com/-/media/files/perspectives-events/publications/2020/07/gpos–not-just-for-the-healthcare-industry.pdf.

The federal government could also drive state adoption by conditioning some or all of federal transportation grants on the purchase of low-carbon materials. Even without conditional federal funding, states can take the lead by requiring public works and state-funded projects to incorporate a certain percentage of low-emissions cement. Governments can also promote low-carbon cement through procurement strategies such as contracts-for-differences (CfDs), preferential bidding treatment, contract bonuses, and "Buy Clean" initiatives. The Federal-State Buy Clean Partnership, which includes the federal government and 13 states, exemplifies efforts to prioritize low-carbon construction materials in public procurement.[328]

CfDs are a financing approach where the a buyer agrees to purchase an asset, such as low-carbon cement, and pay the seller the difference between the future market value of that asset and a predetermine value or "strike price" set at the time the contract was initiated; however, if the market price is higher than strike price at the time of the sale, the seller pays the buyer the difference. A guaranteed premium for low-carbon cement market helps offset production costs, while the potential for upside benefits limits the buyer's risk. CAIA, the legislation described in **Section 4.5**, proposed to create a similar mechanism that, if passed, would have allocated $15 million for the Federal Highway Administration to establish a state-run program reimbursing states for the additional cost of using low-emission materials cement, concrete, asphalt, or asphalt binder in highway projects.[329]

Another option is incentivizing contractors with bidding bonuses for incorporating low-carbon cement.[330] Some states already offer bidding discounts during public project reviews to reward lower-carbon materials. For example, the top bid might receive a 5–10 percent base price discount for bid evaluation, with smaller discounts applied to other bids based on their relative carbon performance. The contractor that uses lower-carbon cement would benefit by having a more competitive bid compared to bids that rely on traditional carbon-intensive cement. Additional discounts could further encourage the adoption of emerging technologies with high decarbonization potential.

Gaps and barriers

Many government procurement models require that the government and suppliers mutually agree to a price for delivery of a future good. While the government would not be financially obligated if the supplier failed to deliver at the agreed quantity or specifications, the supplier may pull out of the agreement if their actual costs exceed the previously negotiated price minus any penalties for failure to meet supply obligations. Any federal or state program would have to be funded at a level that would attract suppliers into the market and with a strike price that is not so low as to discourage investment. Additionally, as with other policy approaches, government procurement models face challenges associated with the regionalized and fragmented nature of cement and concrete markets. Any CfD or procurement model would have to account for regional differences in cement production costs and supply and be targeted far enough upstream in the value chain to avoid the cost of negotiating with myriad entities in the "fragmented middle." This can be a challenge in practice, as the ultimate customer (e.g., federal and state transportation departments) rarely deal directly with cement producers. The further down the value chain a CfD or other procurement model is established, the less ability there is to influence actions of producers.

Cost to implement

The primary cost for government procurement models is the premium paid on low-carbon cement, which can vary with market conditions. The administrative costs associated with a CfD and other contracts that preestablish pricing are relatively low and primarily associated with negotiating a single strike price across multiple suppliers. A contract bonus bidding program requires less negotiation and thus reduces administrative challenges. Innovative procurement programs should include a modest investment in workforce training for procurement officers responsible for verifying low-carbon products that are bid and used in government projects.

328 The White House. 2023. Federal-State Buy Clean Partnership Principles. Available at: https://www.sustainability.gov/pdfs/federal-state-partnership-principles.pdf

329 S.3439, *Concrete and Asphalt Innovation Act of 2023.*

330 New York State and New Jersey proposed Low-Embodied Carbon Concrete Leadership Act. *See also* "New Jersey Adopts First-of-a-Kind Low Carbon Concrete Law." NRDC (Jan. 31, 2023).

Implementation risks

The greatest risk in implementing low-carbon cement procurement programs is settling the strike price either too low, which inhibits investment, or too high, which increases costs unnecessarily. Another challenge is the possibility that low-carbon embodied products may not be commercially available when needed. However, compared to R&D funding and pilot programs that have no assurance of commercialization, CfDs and other government procurement models are relatively low risk because they only pay for low-carbon products that are actually delivered.

Innovative procurement methods must be evaluated periodically to ensure they ultimately catalyze market transformation. To avoid providing unnecessary windfalls for technologies that achieve market commercialization and make gains in cost-competitiveness, strike prices must be decreased toward the market price or contracts must enforce more stringent emission requirements.

Impact

As the largest purchasers of cement, federal and state governments have significant leverage to drive markets toward lower-carbon alternatives. Federal and state government purchased 45 million metric tons of cement in 2018.[331] If all this cement was 25 percent less carbon-intensive than the industry benchmark of 0.83 tons of CO_2e per metric ton (see **Table 3**), this would represent 9.3 million metric tons of CO_2 savings. Moreover, by encouraging the industry to develop cost-competitive, less carbon-intensive products, governments can drive down the premium over time, making low-carbon cement more attractive to private sector consumers. The construction industry operates on tight margins and is highly competitive, so government signals are particularly impactful.

Carbon advantage tariff with reinvestment

A carbon-based tariff would tax imported products that are more carbon intensive than domestically produced alternatives to incentivize domestic consumption, encourage foreign suppliers to reduce their product emissions intensity, and provide revenue that could be reinvested into domestic decarbonization. RD&D is a particularly salient reinvestment strategy, as it can increase domestic competitiveness and further decrease emissions. Several Congressional bills have been introduced by sponsors spanning the political spectrum: the *American Opportunity Carbon Fee Act* (S.1128), the *Foreign Pollution Fee Act* (S.3198), and the *Clean Competition Act* (S. 3422), and the *FAIR Transition and Competition Act* (H.R.4534).[332] The European Union is in the process of implementing a carbon advantage tariff—the Carbon Border Adjustment Mechanism (CBAM)—which includes cement.[333] This places a carbon-based tariff on imported cement equal to what EU-based cement producers pay through the Bloc's emissions trading scheme price while reducing the current free allowance scheme.

Gaps and barriers

Any carbon-based tariff likely requires an act of Congress. While the current global trade paradigm is more receptive to tariffs, there is potentially less support for tariffs that would raise the price of necessary commodities such as cement for the purpose of encouraging emissions reductions in that sector. More problematic is that U.S. cement is more carbon-intensive than cement imported from our major trade partners, with Canada being one notable exception; this fact nearly eliminates any potential for influencing foreign markets or creating revenue streams to incentivize domestic decarbonization.

Cost to implement

The cost to implement a carbon tariff could be high. It requires establishing a national product carbon intensity baseline, developing foreign or firm-specific baselines, comparing foreign to domestic products on a like-for-like basis, and then taxing those foreign imports appropriately at the border. Funds raised, if specifically earmarked for reinvestment, must also be managed for that purpose. The administrative costs of implementation are likely higher than for other policy approaches discussed in this whitepaper.

331 Hasanbeigi, A., D. Shi, H. Khutal. 2021. "Federal Buy Clean Policy for Construction Materials in the United States." Global Efficiency Intelligence. Available at: https://www.aceee.org/sites/default/files/pdfs/ssi21/panel-4/Shi.pdf.

332 A complimentary bipartisan bill, the PROVE IT Act (S.1863) would require the U.S. government to comprehensively assess the carbon intensity key commodities in major economies, establishing a carbon-intensity benchmark for future carbon advantage tariffs.

333 See EU CBAM regulation at: https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en.

Implementation risks

The major implementation risk is compliance with World Trade Organization General Agreement on Tariffs and Trade (GATT) provisions which aim to ensure equal treatment between domestic and imported goods.[334] GATT allows only narrow exceptions, none of which currently include carbon intensity explicitly. There are risks if the policy is successful: the United States imports roughly one-quarter of all cement it consumes, which suggests tariffs could increase domestic prices substantially. Depending on the statutory requirements for reinvestment, funds raised through the tariffs may or may not help to reduce that price impact.[335]

Impact

The near-term impact of a carbon advantage tariff for cement would be small, given that U.S. cement is more emission-intensive than most imports. Canada is the United States' only major trade partner with higher emission cement, and only by a margin of 0.05 tons CO_2e per ton of cement. The 4.9 million tons of Canadian cement imported per year would garner approximately $50 million dollars in tariffs, assuming carbon advantage pricing is set at the EPA's social cost of carbon ($212 per metric ton CO_2e in 2025, using a 2 percent real discount rate).[336] $50 million does not go far toward installing low-carbon cement infrastructure; it is less than the lowest award under the Industrial Demonstrations Program ($62 million).

5.3 Regulatory Approaches

Low-carbon standards

Low-carbon standards aim to reduce GHG emissions by setting embodied carbon thresholds for cement and concrete used in public construction projects. This approach encourages the adoption of low-carbon cement alternatives and relies on EPDs to assess the environmental impact of materials. States and local governments can implement these standards by requiring contractors to submit EPDs with their bids and by establishing maximum allowable GHG emissions for materials used in state-funded projects.

Gaps and barriers

As of now, only a few states, including California, Colorado, New York, New Jersey, Oregon, and Maryland, require EPDs for certain construction materials. This limited adoption reduces the overall impact of low-carbon standards. Developing EPDs can be costly and complex, particularly for smaller contractors who may lack the necessary resources and expertise. This could lead to reduced competition and higher project costs. Implementing low-carbon standards will also require training for contractors and government agencies to effectively develop, interpret, and utilize EPDs. Without adequate workforce development, the adoption of these standards may be hindered or confidence in the policy eroded. Finally, the availability of low-carbon cement alternatives may not meet the immediate demand created by stringent standards, potentially leading to supply constraints and increased costs.

Cost to implement

Implementing low-carbon standards at the federal level would primarily involve administrative costs related to policy development, oversight, and enforcement. GSA has already initiated steps by requiring EPDs for concrete and asphalt materials in federal projects. Other agencies, such as the Federal Highway Administration could partner with GSA to expand the use of low-carbon standards into other project types.

States would incur similar administrative costs, including expenses for developing standards, training personnel, and monitoring compliance. Additional costs may arise from providing support to local suppliers or contractors in developing EPDs.

Implementation risks

If low-carbon materials are not properly vetted, there is a risk of compromising structural integrity, leading to potential safety issues. Ensuring compliance across numerous projects and contractors can be complex, requiring robust monitoring and verification systems. There may be opposition from industry stakeholders due to perceived increases in costs and changes to established practices.

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334 Many international trade scholars dispute whether a carbon-based tariff would violate GATT principles. For more on the EU CBAM, U.S. carbon-based tariff efforts, and potential WTO concerns see *Border Carbon Adjustment: Background and Development in the European Union.* Congressional Research Service (Feb. 21, 2023).

335 Existing tariffs in the U.S. flow to the general fund rather than being earmarked for specific purposes. Congressional Research Service (CRS). Updated 2025. U.S. Tariff Policy: Overview. Available at: https://crsreports.congress.gov/product/pdf/IF/IF11030.

336 EPA. 2023. "Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances." Available at: https://www.epa.gov/system/files/documents/2023-12/epa_scghg_2023_report_final.pdf.

Impact

The abatement potential for low-carbon standards could be large, depending on how the standards are set and in what jurisdictions. A well-designed policy could ratchet the emission standard threshold down over time, drawing the market toward lower-carbon alternatives over time as supply improves.

Construction regulations

Construction regulations aimed at optimizing concrete use focus on enhancing design efficiency and promoting the reuse of concrete elements in building projects. These measures are intended to reduce the overall demand for concrete, thereby decreasing associated GHG emissions. Strategies include topology optimization, lean design, alternative structural solutions, reuse of concrete components, and extending building lifespans. Collectively, these approaches could lead to a significant reduction in cement-related emissions by 2050, even if the emission intensity of cement remains unchanged.

Gaps and barriers

A key hurdle to adopting construction regulations is regulatory fragmentation. Building codes and construction standards vary considerably across federal, state, and local levels, leading to inconsistent adoption of optimized concrete use practices. This fragmentation can hinder widespread implementation of efficiency measures.

Stakeholders such as building owners, designers, and construction companies may resist changes due to concerns over liability, perceived risks associated with new design methodologies, and potential impacts on project timelines and costs. Further, there is a general lack of awareness and expertise regarding advanced design optimization techniques within the construction industry. This knowledge gap can impede the adoption of efficient design practices. Additionally, initial costs associated with implementing design optimization tools and training programs may deter stakeholders, despite potential long-term savings and environmental benefits.

Cost to implement

Implementing optimized concrete use regulations at the federal level would involve costs related to developing and updating building codes, conducting nationwide training programs, and establishing monitoring and enforcement mechanisms. These costs are estimated to be low-to-moderate, given the scale of federal operations, established protocols for periodically updating construction codes, and the potential for economies of scale. The DOE's Building Technologies Office within the Office of Energy Efficiency and Renewable Energy provides a comprehensive suite of technical and support services for the development, adoption, and enforcement of building energy codes; this Building Energy Codes program operates with an annual budget of $15 million. Incorporating codes for enhanced design efficiency and materials reuse into the office's purview would capitalize on existing competencies and would require a relatively small increase in the overall program budget. At the state level, costs would include adapting federal guidelines or national codes to local contexts, conducting state-specific training sessions, and setting up compliance monitoring systems. These expenses are expected to be lower than federal costs but will vary depending on the state's size and existing infrastructure.

Implementation risks

The greatest risk to adoption of cement construction regulations is misapplication or misunderstanding of optimized design principles, which could lead to structural failures, posing safety risks and potential legal liabilities. Another challenge is ensuring compliance across diverse jurisdictions with varying levels of resources and expertise.

Impact

If effectively implemented, construction regulations promoting efficient concrete use could lead to substantial GHG emission reductions (up to 22 percent according to one study. By decreasing the demand for cement, these measures could contribute to a significant decrease in the construction sector's carbon footprint by 2050.

Performance-based material standards

Performance-based material standards in the cement industry emphasize defining material performance requirements, such as compressive strength and durability, without prescribing specific compositions. This approach contrasts with traditional prescriptive standards that dictate exact formulations and material proportions. While performance-based standards can promote innovation and the adoption of low-carbon alternatives, several gaps and barriers hinder their widespread implementation.

Gaps and barriers

Limited acceptance for use in government procurement is a key impediment to performance-based specifications. Despite the introduction of ASTM C1157 in 1992, the subsequent three decades have seen halting adoption of performance-based material standards. A 2022 survey found that only 7 out of 36 surveyed state transportation departments had incorporated performance-based specifications into their concrete standards.[337]

State transportation departments often exhibit risk aversion, favoring established prescriptive standards over newer performance-based approaches. This cautiousness stems from concerns about ensuring safety, durability, and long-term performance of infrastructure projects. Even states with statutory commitments to reductions in GHG emissions may deem a switch to performance-based material standards to be unacceptable due to perceived risks of infrastructure failure and associated financial liability.

Other barriers to adoption include training, testing, and validation. Transitioning to performance-based material standards necessitates comprehensive training for contractors, engineers, and inspectors. Many agencies lack the resources and programs required to effectively implement and verify new formulations under these standards. Further adequate testing and modeling equipment are essential to assess and ensure that cement and concrete products installed in accordance with performance-based standards meet safety requirements. Many state transportation departments and contractors lack access to such resources, hindering the adoption of innovative materials.

Cost to implement

Implementing performance-based standards at the federal level would involve costs associated with revising national standards, developing comprehensive training programs, and investing in testing infrastructure. These initiatives would require substantial funding to ensure nationwide consistency and effectiveness. Notably, the Federal Highway Administration has an ongoing Accelerated Implementation and Deployment of Pavement Technologies (AIDPT) Program, which seeks to advance the use of low-carbon materials:

> *The AIDPT activity will advance strategies for lowering the embodied carbon of paving mixtures and provide tools and information to quantify these strategies. Performance tests to better characterize the durability of materials and pavements will continue to be deployed and implemented. Implementation activities include providing education and guidance on the use of new tests, support for demonstration and shadow projects (where new technologies are used alongside existing technologies), and other information-sharing opportunities such as peer exchanges and workshops.*[338]

AIDPT was allocated $12 million annually under the Bipartisan Infrastructure Law to advance such strategies, including demonstration grants to state and local transportation agencies as well as direct and indirect assistance to implement new innovations and technologies. Maintaining this funding over time in a new political environment will be key to ensuring the success of the multi-year undertaking.

At the state level, costs would include updating state-specific standards, conducting training sessions for local agencies and contractors, and procuring necessary testing equipment. The financial burden would vary depending on the state's existing infrastructure and resources but could be substantial, especially for states with extensive transportation networks. With similar funding to FHWA's AIDPT Program—$12 million annually—a coalition of states could collaborate to advance the use of performance-based material standards for concrete and other transportation materials with attention to state-specific conditions and constraints.

Implementation risks

Among the greatest risks to implementation is industry resistance. The cement and construction industries may oppose changes due to potential disruptions in established supply chains and the need for new quality assurance processes. Further, without federal mandates, the adoption of performance-based standards may be inconsistent across states, leading to a fragmented approach that could undermine the policy's overall effectiveness. Finally, there will be technical challenges to overcome. For example, ensuring that new materials meet performance criteria under diverse environmental conditions poses technical challenges that require extensive research and validation.

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337 *NCC Spring 2022 State Reports on Sustainability and Concrete Materials.* 2022. *National Concrete Consortium.* Available at: https://cdn-wordpress.webspec.cloud/intrans.iastate.edu/uploads/2022/04/05-Miller-State-Reports.pdf.

338 United States Department of Transportation. 2023. "Annual Modal Research Plans FY 2023 Program Outlook FY 2024." Available at: https://www.transportation.gov/sites/dot.gov/files/2023-11/AMRP%20FY2023-2024%20FHWA%20S1%20FINAL%2007132023.pdf.

Impact

Transitioning to performance-based standards can greatly reduce GHG emissions by facilitating the use of SCMs and alternative binders. For instance, increasing SCM content in concrete mixes can lead to substantial emission reductions. Additionally, adopting innovative materials such as LC3 cement can reduce emissions by up to 40 percent compared to traditional Portland cement.

Federal air regulations

EPA already regulates emissions of air pollutants such as particulate matter, nitrogen oxide, and sulfur dioxide from cement plants using its authority under the *Clean Air Act*. To drive GHG emissions reductions in the cement sector, EPA could consider adding CO_2 to the list of pollutants included in the NSPS for Portland cement manufacturing during its next revision of the standards. Statutorily, these standards are to be revised every eight years, although in practice this rarely happens.[339] Once it sets NSPS for CO_2 emissions from cement production facilities, EPA would also need to set standards for existing cement facilities under *Clean Air Act* Section 111(d), as it recently did for electric generating units.

Regulating GHG emissions from cement facilities under the *Clean Air Act* would establish consistent, sector-wide standards. Depending on the stringency of the emissions limit, these regulations could either serve as a policy backstop or a driver of more ambitious emissions reductions. Even if the standards begin in a backstop role, they would likely tighten over time as technological options for decarbonization improve.

Gaps and barriers

EPA does not currently regulate CO_2 under the NSPS for Portland cement manufacturing, nor does it set standards for CO_2 from existing production facilities under Section 111(d). This leaves substantial room for EPA to establish more stringent regulations for GHG emissions from cement plants. As far back as 2010, EPA found that there were likely cost-effective control strategies for GHG emissions from Portland cement manufacturing, but that it needed additional data from cement producers to develop a standard. In its final rule for amendments to the cement NESHAP and NSPS, EPA wrote that:

First, Portland cement is one of the largest stationary source categories of GHG emissions, ranking as the third highest U.S. source of CO_2 emissions. Second, based on our initial evaluation it appears that there are cost-effective control strategies for this source category that would provide an appropriate basis for establishing a standard of performance for GHG emissions…Based upon this preliminary evaluation, the Agency is working towards a proposal for GHG standards form Portland cement facilities. We are not, however, proposing such standards at this time because in order to develop proposed standards we need additional information on site specific factors…To this end, the Agency will be sending out information requests to fill these information gaps so that we are able to propose a standard addressing GHGs in a timeframe that would allow the regulated community to make sound investment decisions in response to these MACT and NSPS requirements.[340]

Despite finding 15 years ago that there are cost-effective control strategies available for GHGs in the cement manufacturing industry, EPA still has not issued a standard regulating them. As EPA wrote in its 2010 rule, one barrier to issuing a CO_2 NSPS for cement plants is that EPA must have enough information to support a rulemaking. EPA could overcome this barrier by sending information requests to industry to gather the necessary data.

In practice, the larger barrier to *Clean Air Act* regulation of GHGs is that this approach relies on executive branch authority and consequently requires a climate-motivated presidential administration to move forward. While this is likely to hinder action in the near term, it could present an opportunity in the future, because a president looking for a way to reduce GHG emissions could use this approach without needing Congress to pass additional legislation.

Cost to implement

EPA's current budget for stationary source regulation provides a benchmark for the magnitude of the public expenditure necessary to regulate GHG emissions from Portland cement manufacturing. EPA's actual FY24 spending for all federal stationary source regulation was $29.8 million.[341] This includes NAAQS, NESHAP,

339 42 U.S. Code § 7412(d)(6).

340 75 Fed. Reg. 54997.

341 U.S. Environmental Protection Agency. 2024. Fiscal Year 2025 Justification of Appropriation Estimates for the Committee on Appropriations: Tab 05 Environmental Programs and Management. Available at: https://www.epa.gov/system/files/documents/2024-04/fy25-cj-05-epm.pdf.

NSPS and other *Clean Air Act* Section 111 regulations, *Clean Air Act* Section 129 regulation of waste combustion, and the *Regional Haze Rule*.

For FY25, EPA requested an increase in budget of $13.6 million (including 38.8 FTE) for implementation of the new Section 111 rules for electric generating units, as well as facilities in the oil and gas sector. This increase is equivalent to 0.1 percent of EPA's total budget request for FY25.[342] The Section 111 rule for electric generating units covers 186 existing coal units,[343] which is over twice the number of cement plants, so administering a similar regulation for cement plants would likely require a correspondingly smaller budget and addition of staff.

Implementation risks

New emissions standards will likely face legal challenges. Recent Supreme Court decisions, including the loss of *Chevron* deference, indicate a trend toward increased scrutiny of administrative rules, including emissions standards. While the *Clean Air Act* delegates to EPA discretion in determining appropriate emissions standards, courts will scrutinize both whether standards exceed statutory authority and whether the technical and scientific basis for the standards is reasonable and adequately explained.

Impact

This mechanism has medium-to-high abatement potential. The initial impact of GHG emissions standards under 111(b) and 111(d) would depend on what EPA determines the BSER is. For example, if EPA determined that 95 percent carbon capture was the BSER for cement facilities, the abatement potential would be as much as 63.4 MMT CO_2 per year once the standard came into full effect.

5.4 Total Capital Expenditures and Policy Costs to Enable Cement Decarbonization

Capital expenditures

One metric that can be used to measure the total expenditure necessary to decarbonize the cement sector is capital formation, which measures outlays on additions to the fixed assets in an industry, plus net changes in the level of inventories.[344] **Table 14** shows DOE's estimate of capital formation necessary to decarbonize the cement sector by 2050. DOE found that total capital formation in the sector from today to 2050 would be between $59 to $120 billion (real 2024$ with 0 percent discount rate) to achieve decarbonization.

The decarbonization pathway that DOE modeled assumed that the industry will construct three to five additional demonstration projects each for CCUS and alternative production methods by 2030, at a cost per project of $500 million to $1 billion, and that the total number of cement plants will increase to 102. During this same period, DOE models all existing cement plants adopting currently deployable alternative fuel, efficiency, and clinker substitution measures at a cost of $36 to $70 million per plant. Total capital expenditures by 2030 will be $5.7 to $17.1 billion.

Between 2031 and 2050, DOE models an incremental 10 plants as being constructed, bringing the total number of cement plants up to 112. DOE models these 10 plants as adopting the same alternative fuel, efficiency, and clinker substitution measures as the existing plants adopted in the 2020s, at the same cost (in real dollars) per plant. DOE further assumes that 102 to 106 plants adopt CCUS or alternative production methods at a cost of $500 million to $1 billion (the 6–10 pilot plants from the 2020s already use these technologies). Total capital expenditures over this time period are $53 billion to $103 billion.

342 U.S. Environmental Protection Agency. 2024. FY 2025 EPA Budget in Brief. Available at: https://www.epa.gov/system/files/documents/2024-03/fy-2025-epa-bib.pdf.

343 U.S. Environmental Protection Agency. 2024. Final Carbon Pollution Standards to Reduce Greenhouse Gas Emissions from Power Plants. Available at: https://www.epa.gov/system/files/documents/2024-04/cps-presentation-final-rule-4-24-2024.pdf.

344 World Bank Group. Metadata Glossary. Available at: https://databank.worldbank.org/metadataglossary/world-development-indicators/series/NE.GDI.TOTL.ZS.

Table 14: U.S. DOE estimate of total capital formation necessary to decarbonize cement sector by 2050

	2025-2030		2025-2030	
	Low	High	Low	High
Total number of cement plants		102		112
CCUS - Demonstration				
Cost per demonstration project ($M)	$500	$1,000		
Number of projects	3	5		
Total cost	$1,500	$5,000		
Alternative Production Methods – Demonstration				
Cost per demonstration project ($M)	$500	$1,000		
Number of projects	3	5		
Total cost	$1,500	$5,000		
Currently Deployable Measures – Deployment				
Alternative fuels and efficiency (capex per plant in $M)	$10	$10	$10	$10
Clinker substitution (capex per plant in $M)	$16	$60	$16	$60
Total plants deployed	102	102	10	10
Total capex cost ($M)	$2,652	$7,140	$260	$700
CCUS or Alternative Production Methods – Deployment				
Cost per deployment (capex per plant in $M)			$500	$1,000
Total plants deployed			106	102
Total capex cost ($M)			$53,000	$102,000
Total capital formation ($M)	$5,652	$17,140	$53,260	$102,700

Policy costs

Notably, the level of technological uptake identified in DOE's *Pathways to Commercial Liftoff: Low-Carbon Cement* will require substantial policy support. **Table 15** shows a high-level estimate of public expenditures over the next decade that will be necessary to lay the groundwork for rapid deployment of decarbonized cement technologies in the late 2030s and beyond. We estimate that total public expenditures from 2026 to 2035 to be $11.4 billion (2024$ with zero percent discount rate) or $10.1 billion with a 2.15 percent discount rate.

Key actions over the next decade include:

- Continuing to fund R&D and pilot project deployment. Based on historical award sizes, we estimate that DOE will require $76 million to fund R&D efforts and $3.9 billion to fund demonstration projects. These estimates are based on historical award sizes from DOE. The total funding requirement for demonstration projects is larger than for R&D because the average award size, even with industry cost-sharing, is $259 million per project, compared to $3.8 million for R&D grants.
- Incentivizing CCUS deployment on cement plants by increasing the tax credit for carbon capture in the cement sector. We model an increased federal tax credit of $143 per metric ton of CO_2 becoming available in 2030, with two cement plants per year installing CCUS equipment. The annual policy cost of the tax credit is low at first and increases over time as more plants adopt CCUS. Total public expenditures through 2035 are $2.7 billion.
- Offering public support for CO_2 infrastructure buildout. We model three years of federal administrative costs to reform the CIFIA application process, followed by a re-appropriation of $2.1 billion to the CIFIA program in 2029, which the government spends over a period of 10 years. The total cost of this program through 2035 is $1.5 billion.
- Establishing a U.S.-based Clean Buyers Association for cement and transparent third-party labeling for low-carbon cement products. These measures have low public costs that are primarily related to policy administration and technical assistance. We estimate that DOE would hire three full-time employees to assist the cement industry with convening a Clean Buyers Association, for a total public cost through 2035 of $8.1 million. Similarly, we assume that the public costs of third-party labeling are primarily administrative, and that the government also offers grants to cement producers to assist them with developing EPDs, for a total policy cost through 2035 of $19.9 million.
- Shifting government procurement to low-carbon cement and establishing advance market commitments to signal the government's long-term level of demand for green cement. We assume that the price premium for low-carbon cement is 30 percent and model state and local governments beginning to procure low-carbon cement in 2027 and the federal government in 2031. As with the tax credit for CCUS, public expenditures are low at first and increase as the amount of low-carbon cement purchased ramps up over time. The total policy cost through 2035 is $2.8 billion (including federal, local, and state procurement). We model the cost of the advance market commitment as being proportional to the amount of low-carbon cement the government procures, for a total policy cost of $45 million.
- Costs for adopting, implementing, and enforcing low-carbon standards, construction regulations, and material performance-based standards include administrative expenses, technical assistance, and equipment costs. Federal, state, tribal, and local entities commonly adopt model building codes and standards from a standards-developing organization by incorporating such model codes or standards into law or regulation by reference. The total policy cost through 2035 is $283 million, which we model as being as fractional increases in budget for DOE EERE Building Technology Office's building energy codes program and the Federal Highway Administration's AIDPT program for low-carbon construction materials.
- Regulating GHG emissions from cement plants under the *Clean Air Act*. We assume that EPA would begin developing these standards in 2030 and estimate that the cost of developing and promulgating the regulations will be $41 million through 2035.

While we assume a lag in the adoption of several federal policies until 2030, earlier adoption of these policies would be advantageous from an emissions-reduction perspective and would shift public expenditures earlier. We primarily model federal spending, but states could also choose to take the lead on many of these policies and establish them earlier than 2030. This would result in earlier emissions reductions and potentially enable more rapid federal adoption of analogous policies once it becomes politically feasible.

Table 15: Public spending on cement decarbonization policies, 2026-2035 (2024$, million)

Approach	Methodology	Total cost (0% discount rate)	Total cost (2.15% discount rate)
Research and Development	Assume that DOE awards two $3.8 grants million per year (based on historical grant sizes).	$76.0	$69.2
Pilot Projects	Assume DOE awards two $259 million grants per year from 2026-2030 and one grant per year thereafter (based on historical grant sizes).	$3,885.0	$3,599.6
Increased tax credit (e.g., 45Q) for carbon capture in the cement industry	Assume that a $143/ton CO_2 tax credit is available starting in 2030, and that two cement plants per year adopt CCUS. The average emissions avoided with 95% carbon capture is 0.70 MMT CO_2 per plant per year.	$2,728.6	$2,345.1
Support for CO**2** infrastructure buildout through CIFIA	Congress appropriated $2.1 billion for CIFIA that will expire in 2026. Assume three years of administrative costs to reform the CIFIA application process. Assume that the administrative cost would be 1.6% of the subsequent annual budget for the program. Assume that Congress will re-appropriate $2.1 billion for CIFIA in 2029, and that the money will be spent over ten years.	$1,480.1	$1,304.9
Clean Buyers Association	Assume that DOE hires three full-time employees to convene the Buyers Association in 2026. The average cost per FTE at DOE is $268,691.	$8.1	$7.3
Government Procurement	Assume that there is a 30% premium for green cement above the national average price of $156 per ton of cement. Annual U.S. cement production is approximately 85.5 MMT per year, of which approximately 25% is procured by the federal government and 17% by state and local governments. Assume that in 2031, the amount of federally procured green cement starts at 10% and increases by 5% per year thereafter. Assume that state procurement follows same trajectory, starting in 2027.	$2,832.2	$2,463.8
Advance Market Commitment	Assume public expenditure for this policy is the administrative cost to establish government market commitments, and that this cost is equal to 1.6% of government procurement costs.	$45.3	$39.4
Third-Party Labeling	Assume that the 92 U.S. cement plants produce on average of 4.3 cement types each, and that the total cost per product to develop an EPD is $33,800. Assume that the cost of public administration and technical assistance is 10% of this total private expenditure. In addition, assume that the government issues grants to 10 cement plants per year to cover half the cost of developing EPDs starting in 2027.	$19.9	$18.1
Low-Carbon Standard	Assume federal spending under the DOE EERE Building Technology Office's building energy codes annual program budget ($15 million) is increased by 10% to include low-carbon standards, beginning in 2030 and extending through 2035.	$42.0	$36.9
Construction Regulation	Assume two states adopt low-carbon standards per year beginning in 2026, with a per-state cost equal to 2% of the federal building energy codes program.	$24.6	$21.5

Approach	Methodology	Total cost (0% discount rate)	Total cost (2.15% discount rate)
Performance-Based Standard	Assume federal spending under the DOE EERE Building Technology Office's building energy codes annual program budget ($15 million) is increased by 10% to include construction regulations enhancing design efficiency and promoting the reuse of materials, beginning in 2028 and extending through 2035.	$216.0	$194.8
Federal Air Regulations	Assume EPA starts developing standards in 2030 and promulgates them 2-3 years later. Cost per year to develop and administer the program is half the incremental cost of administering the 111 Rules for electric generating units.	$40.8	$35.6
Grant Total	**Assume federal spending under the DOE EERE Building Technology Office's building energy codes annual program budget ($15 million) is increased by 10% to include construction regulations enhancing design efficiency and promoting the reuse of materials, beginning in 2028 and extending through 2035.**	**$11,399**	**$10,136**

Discount rate of 2.15 percent based on an inflation-indexed 10-year treasury constant maturity rate, available at: https://www.federalreserve.gov/releases/h15/.

SECTION 6

Policy Recommendations

The section below discusses key actions available to policymakers to address gaps and barriers to adoption of cement decarbonization technologies.

6.1 Financial Support Recommendations

Expand targeted R&D support to low-TRL technologies

Objective: Fund research and development at private companies, national labs, and university materials labs to enable cement decarbonization technologies currently at low TRLs to advance to the point where they are ready for demonstration and eventual commercialization and market take-off.

Key Actions:

Continue funding R&D for early-stage cement decarbonization technologies through offices at DOE including ARPA-E, NETL and IEDO, with a particular focus on technologies that have not received as much public support to date, such as bio-cement and alternative binder chemistries.

Secure funding for pilot and demonstration project investment

Objective: Use federal funding to incentivize and leverage industry investment, enabling construction of pilot and demonstration projects to support higher TRL technologies ready for large-scale demonstration.

Key Actions:

Congressional legislation to secure funding for DOE for additional pilot and demonstration projects, with a focus on methods for producing cement using alternative feedstocks and alternative production methods, as well as additional CCUS demonstrations.

Strengthen policy and regulatory support for CCUS deployment

Objective: Accelerate the deployment of CCUS at cement plants by improving the economics of carbon capture through financial incentives and removing ecosystem barriers related to CO_2 infrastructure availability.

Key Actions:

- Increase 45Q tax credit for the cement industry by $35–75 per metric ton of CO_2 (above its current level of $85 per ton) so that the credit will be high enough to incentivize CCUS at cement plants. The increased tax credit should be specific to industries such as cement with high capture costs to avoid excess policy costs and over-adoption of CCUS in other sectors (e.g., corn ethanol production) that have less-costly abatement technologies available.
- Work with communities to address concerns about CO_2 infrastructure siting and mitigate potential negative impacts to safety, air quality, and groundwater quality.
- Streamline CIFIA program requirements to allow developers easier access to the funding to support CO_2 pipeline infrastructure buildout.
- Finalize PHMSA CO_2 pipeline safety rulemaking.[345]
- Finalize offshore carbon sequestration rules. The IIJA gives the Bureau of Ocean Energy Management the authority to lease areas in the Outer Continental

[345] Note, on January 15, 2025, the Biden administration published a Notice of Proposed Rulemaking for CO_2 pipeline rule. It is unclear at this time whether the Trump administration intends to reissue this NPRM. See U.D. DOT, PHMSA. 2025. "USDOT Proposes New Rule to Strengthen Safety Requirements for Carbon Dioxide Pipelines". Available at: https://www.transportation.gov/briefing-room/usdot-proposes-new-rule-strengthen-safety-requirements-carbon-dioxide-pipelines.

Shelf (OCS) for the injection of CO_2.[346] It is unclear what the status is of this proposed rule-making regarding CO_2 sequestration in the OCS.

- Streamline process for Class VI well permitting to further facilitate buildout of CO_2 infrastructure.

6.2 Market-Based Approach Recommendations

Establish an advanced market commitment for low-carbon cement

Objective: Accelerate adoption and development of low-carbon cement by guaranteeing future markets for producers, while fostering innovation, and reducing carbon emissions across the construction industry.

Key Actions:

- Form a coalition of federal and state governments agencies, private companies (e.g., Amazon, Google, and Microsoft), and industry stakeholders to establish an AMC for low-carbon cement.
- Set clear minimum purchase volumes and price guarantees to de-risk investments and drive producers to adopt low-carbon technologies.
- Secure $1 billion in funding commitments (similar to the Frontier carbon capture model) to support the production and commercialization of at least 5 million tons of low-carbon cement by 2028.
- Reduce supply risk by fostering a diverse range of providers using multiple technologies.
- Establish clear timelines to allow producers adequate time to meet demand.

Foster a U.S.-based clean cement buyers association

Objective: Establish a collaborative platform for large U.S. construction firms to commit to purchasing low-carbon cement, accelerating market adoption, reducing carbon emissions, and leveraging collective purchasing power to create strong market demand, incentivize innovation, and foster competition among producers.

Key Actions:

- Convene major U.S. construction firms (e.g., AECOM, Bechtel, Fluor, and Clark Group) to form a Clean Cement Buyers Association.
- Leverage initiatives like the European-based ConcreteZero for guidance and collaboration.
- Align procurement policies and timelines among large-scale cement purchasers, including private-sector firms and public agencies, to collectively demand low-carbon cement.
- Establish baseline emissions intensity standards and define achievable carbon reduction targets to guide procurement and ensure product quality.
- Partner with environmental non-profits and industry groups to manage the association and set clear goals, standards, and timelines.
- Use collective purchasing power to signal demand to technology developers, encouraging investment in decarbonization pathways.
- Provide financial incentives, such as price premiums, to attract market entrants and foster competition.
- Address potential supply constraints by setting progressive, phased targets for emissions reductions.
- Balance ambition and feasibility in target-setting to maintain market confidence and encourage technology adoption.

Strengthen transparent and verifiable third-party environmental product declarations

Objective: Enhance adoption and reliability of EPDs for cement products by ensuring transparency, verifiability, and ease of use, thereby fostering a robust market for low-carbon alternatives and supporting complementary policy strategies.

Key Actions:

- Require transparent, product- and plant-specific EPDs as a baseline for state and federal government procurement of cement, adhering to ISO 14025 and 21930 standards.
- Federal and state governments should mandate EPDs for all cement products purchased with taxpayer money.
- Develop sector-specific guidelines to ensure comparability of EPDs for different types of cement across various applications.
- Offer tax credits, grants, or subsidies to cement producers, especially small firms, to offset the costs of EPD development and third-party verification.

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[346] Pub. L. 117-58, § 40307.

- Fund workforce training programs to equip the industry and government procurement officers with technical expertise in creating high-quality, verifiable EPDs.
- Promote the use of automated tools, blockchain, and advanced data analytics to streamline EPD generation and verification processes in order to reduce costs and increase accuracy.
- Use EPD data to support additional market mechanisms such as carbon advantage tariffs and contract-for-difference schemes.
- Initiate negotiations with third-party EPD verifiers to expand EPDs' scope to incorporate lifecycle emissions in addition to cradle-to-gate metrics, enabling more comprehensive emissions comparisons.

6.3 Regulatory Approach Recommendations

Low-carbon standards

Objective: Reduce GHG emissions in the construction sector by implementing low-carbon standards that mandate the use of materials with lower embodied carbon in public projects.

Key Actions:

- Mandate the submission of EPDs for construction materials in public procurement processes to ensure transparency and facilitate the assessment of environmental impacts.
- Establish clear and progressively stringent embodied carbon limits for materials used in publicly funded construction projects to drive continuous improvement.
- Offer resources and training programs to assist contractors, especially small- and medium-sized enterprises, in developing accurate and reliable EPDs.
- Encourage the production and availability of low-carbon cement alternatives through incentives, research funding, and partnerships with industry stakeholders.
- Regularly review the effectiveness of low-carbon standards and make necessary adjustments based on technological advancements and market developments.
- Industry-wide decarbonization cannot be achieved solely through efficiency improvements and fuel-switching, so performance standards may be needed to spur investment in transformational technologies.

Construction regulations

Objective: To reduce cement emissions associated with material overuse in the construction sector by implementing regulations that promote the efficient use and reuse of concrete through optimized design and construction practices.

Key Actions:

- Work with building code coalitions and standard-setting organizations such as the International Code Council to develop and promote uniform national building codes that incorporate optimized concrete use practices to ensure consistency across jurisdictions.
- Collaborate with industry stakeholders to address concerns, provide clarity on liability issues, and demonstrate the benefits of optimized design methodologies.
- Invest in training programs for architects, engineers, and construction professionals to build expertise in advanced design optimization and construction techniques.
- Offer financial incentives, such as tax credits or grants, to encourage early adoption of efficient design practices and offset initial implementation costs.
- Establish robust monitoring and evaluation frameworks to assess compliance and measure the effectiveness of implemented regulations in reducing material use in construction.

Performance-based material standards

Objective: Reduce GHG emissions in the cement industry by transitioning from prescriptive to performance-based material standards, thereby enabling the adoption of low-carbon cement alternatives without compromising material performance.

Key Actions:

- Collaborate with standard-setting organizations to continue the advancement of performance-based standards such as ASTM C 1157, enabling greater flexibility in material composition with a focus on adapting to state-specific project conditions and requirements.
- Adopt performance-based standards in federal construction projects to set a precedent and encourage wider acceptance across other government levels and the private sector.
- Encourage state transportation departments to integrate performance-based specifications into their procurement processes, possibly by linking federal funding to the adoption of such standards.

- Develop and fund comprehensive training initiatives for contractors, engineers, and inspectors to ensure proper implementation and verification of performance-based standards.
- Allocate resources to establish or upgrade material testing facilities, providing state agencies and contractors with the necessary tools to assess new materials' performance.
- Fund research through national laboratories and universities to validate the performance and durability of low-carbon cement alternatives under various environmental conditions.
- Encourage collaboration among government agencies, industry stakeholders, and academic institutions to share knowledge, resources, and best practices in developing and implementing performance-based standards.

Federal air regulations

Objective: Regulate GHG emissions from new and existing cement plants using EPA's existing *Clean Air Act* authority.

Key Actions:

- Establish NSPS for CO_2 emissions from new cement plants.
- Establish a 111(d) standard for CO_2 emissions from existing cement plants.
- Improve New Source Review implementation to ensure low-carbon alternatives are fully evaluated during permitting of new and modified cement plants.
- Retain expert political advising and legal counsel to ensure proposed rulemaking is durable in a post-*Chevron* era and resistant to legal challenges.
- Revise standards regularly to help ensure that their stringency increases over time as technology improves.

SECTION 7

Conclusion

Decarbonization of the U.S. cement sector stands as both a formidable challenge and a critical opportunity for climate action, industrial innovation, and economic resilience. As this white paper has detailed, cement is foundational to the nation's infrastructure and economic development, yet its production is responsible for an important share of industrial GHG emissions—accounting for 4.4 percent of U.S. industrial emissions and 1.1 percent of total national GHG emissions. The sector's emissions profile is shaped by both energy-related and process emissions, with nearly 60 percent arising from the calcination of limestone, a process intrinsic to traditional cement manufacturing and not easily addressed through fuel-switching or efficiency improvements alone.

Despite notable progress in energy efficiency and a gradual shift from coal to natural gas, the U.S. cement industry remains more emissions-intensive than many of its global peers. The sector's structure—characterized by a concentrated supply side, fragmented intermediaries, and a demand side heavily influenced by government procurement—creates both barriers and levers for transformative change. The cyclical nature of demand, reliance on spot transactions, and limited access to long-term financing further complicate the path to decarbonization, underscoring the need for coordinated policy interventions and market reforms.

7.1 Technological Pathways: Promise and Limitations

A suite of technological pathways offers the potential to dramatically reduce cement sector emissions. Plant efficiency upgrades, while largely implemented already, offer incremental gains. More transformative are alternative feedstocks and production processes such as electrochemical calcination and the use of industrial byproducts, which could greatly reduce or even eliminate process emissions. Clinker substitution and alternative binder chemistries present near-term, cost-effective opportunities for emissions reduction, though their widespread adoption is constrained by material availability, performance standards, and market acceptance.

CCUS emerges as a pivotal technology, particularly for retrofitting newer, coal- and coke-fueled kilns. While CCUS is nearing commercial readiness, its deployment is hampered by high capital costs, infrastructure gaps (notably in CO_2 transport and storage), and policy uncertainty. Alternative fuels, decarbonized electricity, and emerging biocement technologies further expand the decarbonization toolkit, though each faces unique technical, economic, and scalability challenges. Importantly, demand-side measures—such as concrete recarbonation, circularity, and design optimization—can reduce overall cement demand and emissions, and thus complement supply-side interventions.

7.2 Policy Approaches: An Integrated Portfolio

Achieving deep decarbonization in the cement sector requires a synchronized portfolio of financial, market-based, and regulatory interventions. Financial support—through expanded RD&D funding, pilot project grants, and enhanced tax credits—can de-risk early-stage technologies and catalyze private investment. Market-based approaches, including transparent EPDs, advance market commitments, and government procurement mandates, are essential for creating stable demand and incentivizing the production of low-carbon cement. Regulatory measures such as low-carbon standards, performance-based material specifications, and updated construction codes provide the necessary accountability and market signals to drive industry-wide transformation.

The report's policy recommendations emphasize the importance of:

- **Scaling CCUS and alternative feedstock demonstrations** at priority plants, particularly in regions with high emissions intensity and coal dependence.
- **Aligning federal and state procurement policies** with robust, verifiable EPDs to ensure that public spending drives market transformation.
- **Bridging infrastructure and workforce gaps** through targeted investments in CO_2 transport and storage networks, as well as regional training programs for CCUS and low-carbon cement production.
- **Prioritizing local community benefits** by ensuring that decarbonization investments deliver tangible benefits to disadvantaged communities and mitigate local pollution impacts.

7.3 Investment and Implementation: The Road Ahead

The transition to a net-zero cement sector by 2050 will require substantial capital investment—estimated at $69–$120 billion through 2050 for new production facilities and CCUS retrofits—that should be catalyzed by $11.4 billion in public spending on supporting policies over the next decade. These investments are justified by the sector's centrality to infrastructure, the relatively modest impact of higher cement prices on overall construction costs, and the broader societal benefits of reduced GHG and co-pollutant emissions.

A phased implementation roadmap is essential:

- **By 2028**: Finalize low-carbon procurement mandates, deploy regional CCUS infrastructure hubs, and update material performance standards.
- **By 2035**: Achieve 40 percent sector-wide emissions reduction through CCUS retrofits and scaling of alternative production processes.
- **By 2050**: Complete the transition to net-zero production methods, supported by a skilled workforce and mature CO_2 transport and storage networks.

7.4 Final Reflections

The decarbonization of the U.S. cement sector is not only technically feasible but also economically and socially imperative. The convergence of technological innovation, policy momentum, and growing market demand for low-carbon materials creates a unique window of opportunity. However, success will depend on the ability of policymakers, industry leaders, and stakeholders to act decisively—bridging policy gaps, overcoming regional disparities, and ensuring that the benefits of decarbonization are equitably shared.

Failure to act risks locking in high-emission infrastructure for decades, undermining national climate goals, and missing a critical opportunity for industrial leadership. Conversely, a bold, coordinated approach can position the U.S. cement industry at the forefront of global decarbonization efforts, delivering cleaner air, healthier communities, and a more resilient economy for generations to come.