U.S. DEPARTMENT OF ENERGY

Pathways to Commercial Liftoff: Low-Carbon Cement

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Comments

The Department of Energy welcomes input and feedback on the contents of this Pathway to Commercial Liftoff. Please direct all inquiries and input to Liftoff@hq.doe.gov. Input and feedback should not include business-sensitive information, trade secrets, proprietary or otherwise confidential information. Please note that input and feedback provided are subject to the Freedom of Information Act.

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Purpose of this report

These Pathway to Commercial Liftoff Reports aim to establish a common fact base and ongoing dialogue with the private sector around the path to commercial Liftoff for critical clean energy technologies across core U.S. industries. Their goal is to catalyze more rapid and coordinated action across the industry and the full technology value chain.

This Pathway to Commercial Liftoff report specifically focuses on decarbonizing cement production. It is one report in a multi-part series focused on industrial decarbonization. The Industrial Decarbonization Liftoff series provides an overview of the pathways to decarbonization across the eight industrial sectors of focus in the Inflation Reduction Act (IRA[1]): chemicals, refining, iron and steel, food and beverage processing, pulp and paper, cement, aluminum, and glass.[i] DOE has conducted deep analysis and developed reports in the Liftoff series focusing on chemicals & refining and cement. All other industrial sectors have been covered in the Pathway to Commercial Liftoff: Industrial Decarbonization report.

1 Inflation Reduction Act of 2022, Pub. L. 117–169, 136 Stat. 1818 (2022)

Glossary

Term	Definition
ARL[2]	Adoption readiness level (1–9); Represents important factors for private sector uptake beyond technology readiness, including value proposition, market acceptance, resource maturity, and license to operate
CAGR	Compound annual growth rate
CAPEX	Capital expenditure
CCUS[3]	Carbon capture, utilization, and storage
Commercial Liftoff	"Liftoff" represents the point where solutions become largely self-sustaining markets that do not depend on significant levels of public capital and instead attract private capital with a wide range of risk
Demonstration stage	Technology in a stage of the RDD&D continuum where the objective is to determine the technical and commercial feasibility of new technologies
Deployable stage	Technology in a stage of the RDD&D continuum where the objective is to develop commercial deployments
DOT	Department of Transportation (state or federal)
EEJ	Energy and environmental justice
Embodied carbon	Emissions released during the life cycle of a material, including through extraction of raw materials, manufacturing, transportation, utilization, and end of life
EPD	Environmental product declaration (assessment and declaration of a product's environmental impact, particularly its embodied carbon content)
FECM	DOE Office of Fossil Energy and Carbon Management
FOAK	First of a kind
GCCA	Global Cement and Concrete Association
IEDO	DOE Industrial Efficiency and Decarbonization Office
IRA	Inflation Reduction Act of 2022 (Pub. L. 117-169)
KTPA	Thousand tonnes per year
LCA	Life cycle assessment (assessment of environmental impact, particularly emissions, from a product's full life cycle)
MTPA	Million tonnes per year
NOAK	Nth of a kind

2 Adoption Readiness Levels (ARL): A Complement to TRL | Department of Energy

3 This report typically refers to "Carbon Capture, Utilization, and Sequestration" (CCUS) because of the significant potential for carbon utilization approaches in cement and construction materials. Where only sequestration is considered, "CCS" is used. Where only utilization is considered, "CCU" is used.

Term	Definition
NPV	Net present value
OPC	Ordinary Portland Cement (traditional Portland cement formulation, typically composed of ~95% clinker and ~5% gypsum)
OPEX	Operating expenditure
PCA	Portland Cement Association
PLC	Portland Limestone Cement (blended cement in which up to 15% of clinker is substituted with ground limestone)
RDD&D	Research, development, demonstration, and deployment (RDD&D) continuum—defines the path to commercialization where a technology starts as an innovative idea in research, moves to development where the first prototype is created, proceeds to demonstration where the solution is tested in the real world and ending with commercial-scale deployment. Although RDD&D is a continuum, the pathways across stages are not always linear, and technologies may need to go back to earlier stages to be refined.
R&D / Pilot stage	Technology in a stage of the RDD&D continuum where the objective is to discover and determine the technical feasibility of new technologies in a lab or in small pilots
TRL[4]	Technology readiness level (1–9); Metric used for describing technology maturity. It is a measure used by many U.S. government agencies to assess the maturity of evolving technologies (e.g., materials, components, devices) before incorporating that technology into a system or subsystem
45Q	Tax incentive that encourages carbon capture, utilization, and storage (CCUS) projects
45V	IRA tax incentive that encourages the production of clean hydrogen

4 Technology Readiness Assessment Guide | Department of Energy

Executive Summary

The U.S. cement industry must accelerate decarbonization progress dramatically to keep pace with sector-wide net-zero goals. Cement represents ~7–8% of global CO2 emissions and ~1–2% of U.S. CO2 emissions (~70 MT CO2 /year). [ii, iii] Scaling green cement will be critical for the U.S. to achieve net zero overall and will position the U.S. to lead global efforts to decarbonize the sector, including through deployment of U.S.-developed technologies.

Many potential decarbonization approaches are emerging, but nearly all are in pilot stage today in the U.S. and face challenging paths to scale. Combined investment across these approaches would need to reach ~$5–20B cumulatively by 2030 and ~$60–120B cumulatively by 2050 to achieve Liftoff of key technologies and then full decarbonization of the cement industry: [5]

- **An initial set of clinker substitution approaches, alternative fuels, and efficiency measures could abate ~30% of emissions by the early 2030s and ~40% by 2050, while delivering $1B+ of annual savings to industry, if deployed aggressively.**[6] These approaches are broadly high TRL, deployment-ready, and economically viable today.[7] Scale-up could represent a capital formation opportunity of ~$3-8B.
- **Abating the remaining ~60-70% of emissions by 2050 will require approaches that have more difficult economics and still must be demonstrated at commercial scale—namely, carbon capture, utilization, and storage (CCUS) on existing infrastructure and alternative cement production methods.**[8] CCUS could require ~$35–75 in cost improvements or additional revenue per tonne of CO2 and ~$25–55 per tonne of cement to be economically viable with the 45Q tax credit,[9] though there is potential for alternative carbon-capture technologies at lower TRL today to achieve significant cost reductions. Alternative production methods could require $0.5–1.0B in capital expenditure (CAPEX) per plant and still need to validate technology performance and business models at commercial scale. Deployment of these technologies to decarbonize the full cement industrial base could represent a ~$55–110B total capital formation opportunity by 2050.
- **Other measures, including alternative binder chemistries to traditional cements, remain more nascent** and must achieve further technological maturity, improved economics, and customer acceptance to deploy.

Liftoff for all technologies will hinge on creating a strong demand signal from coordinated low-carbon procurement—a signal that may come from the government through public procurement. This demand signal will be vital to incentivize the rapid uptake of new technologies, drive aggressive deployment, and mobilize capital at the required scale. Half of U.S. cement demand is driven by federal and state procurement. [iv, v] With their commanding market share, government agencies and large private buyers are in the leading position to send this demand signal and transform the market.

Supported by low-carbon procurement, technologies could follow four parallel 'tracks' to Liftoff by 2050:

- **Rapid scale-up of clinker substitution, alternative fuels, and efficiency measures from 2023 through the early 2030s,** accelerated by low-carbon procurement standards and high-profile demonstrations of low-clinker cement and concrete blends.

5 Capital formation sizing methodology is available in the appendix.

6 Further scale-up of these technologies through 2050 could abate ~40% of emissions.

7 In general, this report assumes projects and technologies are economically viable if they can clear a 10% internal rate of return and/or are competitive economically with existing production methods and products.

8 This report typically refers to "Carbon Capture, Utilization, and Sequestration" (CCUS) because of the significant potential for carbon utilization approaches in cement and construction materials. Where only sequestration is considered, "CCS" is used. Where only utilization is considered, "CCU" is used.

9 Based on modeling for CCS specifically. CCU is also considered in the body of the report.

- **Full-scale deployment of CCUS retrofits starting in the 2030s**, following initial commercial-scale demonstrations in the mid-to-late 2020s. This deployment would be propelled by coordinated procurement from government and large private buyers, structured to enable investment at the multibillion-dollar scale required.
- **Commercial-scale deployment of alternative production methods for traditional cement products in the 2030s**, likewise following initial demonstrations and with multibillion-dollar capital formation enabled by coordinated procurement.
- **Longer-term scale-up of fundamental alternatives to traditional cement chemistries**, beginning in non-structural, pre-cast, and lower-risk niches and building market share on a longer timeline as standards are updated, market comfort grows, and supply becomes increasingly reliable.

Other emerging technologies are further out from commercialization, but offer promising opportunities for ongoing R&D investment.

Internationally, including in the developing world, pathways to cement decarbonization hinge on large-scale deployment of technologies like CCUS that today are prohibitively expensive outside of wealthy countries. **The U.S. is particularly well-positioned to commercialize and export two business models that could be transformative for global cement decarbonization:**

- **Low-cost CCUS** enabled by a combination of cost reductions from learning effects, commercialization of alternative low-cost capture technologies, and high-value carbon utilization applications.
- **Alternative low-carbon production methods and alternative chemistries** that can achieve cost-parity with or even cost-advantage over traditional cement plants.

Figure ES.1. Four-track pathway to Liftoff

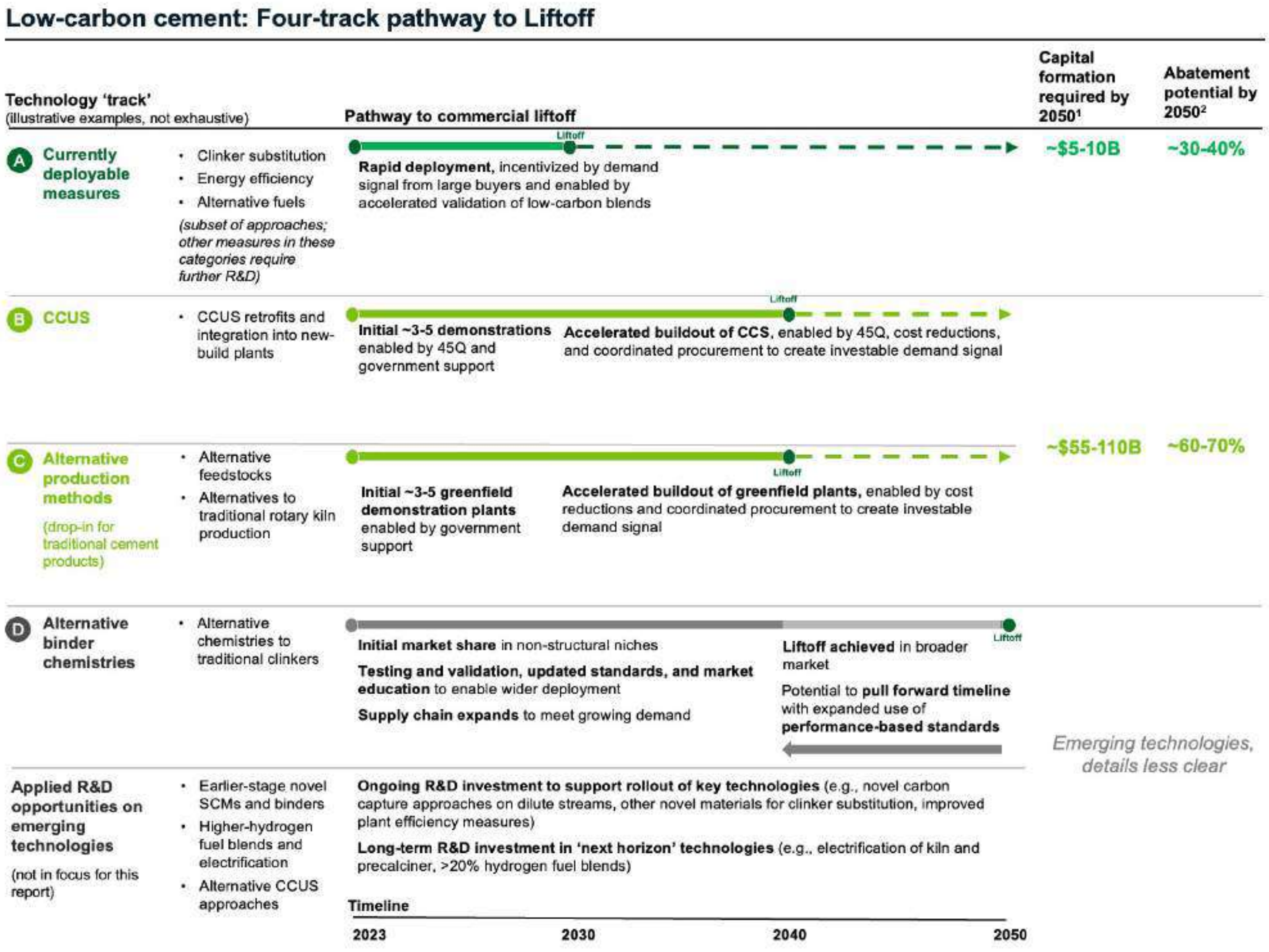


Figure ES.1: Liftoff pathway for the cement sector is split across technologies with varying technology readiness levels (TRLs) / adoption readiness levels (ARLs) and distinct economic, market, and policy constraints and enablers. Four parallel 'tracks' are outlined for different technology types. Other technologies are on a longer timeline and require continuing R&D investment to achieve demonstration and deployment readiness. Track A measures can abate ~30% of emissions by the early 2030s and ~40% of emissions by 2050, while the remaining ~60-70% of emissions will require other technologies in Tracks B, C, and D.
Notes: 1. Capital formation opportunity was estimated according to the methodology detailed in Appendix C and is based on the estimated CAPEX requirement to scale both currently deployable measures and CCUS or alternative production methods across the entire footprint of U.S. cement plants. 2. Abatement potential was estimated using the methodology detailed in Appendix A and assumes the first 30–40% of emissions can be abated by a deployment-ready subset of clinker substitution, alternative fuels, and efficiency measures, with the remaining 60–70% addressed by CCUS and alternative production methods.

Six key challenges must be overcome to scale technologies:

1. The market lacks uniform standards to define low-carbon materials and enable informed procurement.
2. The sector has a ~10 to 20-year adoption cycle for new blends and materials—both from long lead time needed to update standards and a long customer-adoption cycle.
3. The current procurement model is not structured to attract capital at required scale.
4. Decarbonization approaches may come with structural cost increases.

5. Key technologies have performance and cost uncertainty. Others are at lower TRLs and must make further R&D progress to deploy.
6. Projects may lack support from local communities and the public (particularly CCUS projects because of environmental and safety concerns).

Challenges are real but solvable. Six priority solutions could be pursued:

1. Establish shared standards and data ecosystem for low-carbon products.
2. Make targeted interventions to compress the adoption cycle for new blends and materials to ~5–10 years, including:
   - Investing in accelerated testing and validation,
   - Engaging key customers to facilitate the expanded use of low-carbon materials, including adopting performance-based standards, and
   - Providing technical and financial assistance to facilitate adoption in the broader value chain (e.g., small ready-mix companies, subcontractors).
3. Develop alternative procurement models that provide cement projects with firm, long-term offtake commitments to attract risk-averse capital.
4. Develop policy and market models that offset structural costs, including:
   - Providing policy support to offset challenging economics,
   - Supporting premiums with coordinated procurement in the public and private sectors, and
   - Requiring the use of low-carbon materials in construction regulations.
5. For pre-deployment technologies, provide continuing support to accelerate progress along the RDD&D continuum, including:
   - Supporting early project development and creation of archetypal business models and terms for technologies at a higher TRL today, and
   - Continuing to invest in transformative R&D for technologies at a lower TRL today.
6. Implement robust community benefits plans and agreements that are responsive to public concerns, mitigate potential harms, and ensure accountability.

DOE, together with other federal agencies and state and local governments, has tools to address many of these issues and is committed to working with communities and the private sector to accelerate the deployment of green cement technologies, establish the U.S. as a global leader in cement decarbonization, and meet the country's climate, economic, and environmental justice goals.

Government action will play a critical role in validating new approaches and creating strong demand signals. Bold action is also needed by the private sector, including producers, large-scale customers, and financial institutions, which fund them both, to scale these technologies and fundamentally transform the industry. Companies that move first will be best positioned to capitalize on the potential opportunity to capture demand from low-carbon procurement and position themselves to compete in a decarbonized market.

Chapter 1: Introduction

To decarbonize the sector by 2050, the U.S. must deploy novel technologies at all 98 existing U.S. cement plants and at all new-build plants. [vi] New technologies must also be exported internationally to address the ~7–8% of global CO2 emissions from cement. [vii] This report provides a "Pathway to Liftoff" for these key technologies. “Liftoff” represents the point where solutions become largely self-sustaining and can achieve commercial scale without depending on significant levels of public capital, instead attracting private capital with appetite for a wide range of risk.

- **Chapter 2** provides an overview of the current state and emissions profile of the U.S. cement industry, emerging technologies for decarbonization, and structural factors shaping deployment potential.
- **Chapter 3** outlines technology-specific business models, economic and other market dynamics, and the ‘tracks’ different technologies could follow to scale.
- **Chapter 4** addresses current challenges and potential solutions to unlock Liftoff.
- **Chapter 5** outlines key metrics and milestones along the Pathway.

This report is informed by 60+ interviews and conversations with experts and stakeholders from 40+ companies and organizations. Interviewees cover the entirety of the market ecosystem, including large cement and building-materials companies, start-ups, trade associations covering all major segments of the value chain, investors, and federal and state agencies that are large consumers of cement and concrete. All insights have been aggregated and anonymized so as not to be reflective of any single company or other stakeholder. Additional insight is provided by DOE experts, published studies, and decarbonization roadmaps by DOE, other government agencies, and various industry and third-party academic and research organizations.

This report focuses chiefly on decarbonizing primary cement production (i.e., the measures taken inside the fence line of cement plants), but it will be vital to decarbonize the concrete and construction value chain more broadly and look at emissions over the full life cycle of cement and concrete products.

This effort is technology- and business-model agnostic. It is not meant to comprehensively evaluate all potential technologies and business models that could be deployed. A vast array of different technologies may ultimately develop to meet the needs of a net-zero sector. Indeed, 40+ start-ups were identified in this sector alone, in addition to the various approaches under consideration by already-established cement players.

This report draws on and complements DOE’s existing Industrial Decarbonization Roadmap by extending its deep dive into cement and further exploring the market and economic dynamics implicated in a rapid scale-up. Likewise, this report complements many ongoing efforts across federal and state governments to accelerate these technologies' development, commercialization, and deployment.

Chapter 2: Current state and decarbonization challenge

Key takeaways

- **Cement production accounts for ~7–8% of global CO_2 emissions and ~70M tonnes (~1%) of U.S. CO_2 emissions per year**. Decarbonizing the sector will be critical for achieving net zero. By developing, deploying, and commercializing the key technologies domestically and exporting them internationally, the U.S. can take a leading role in global decarbonization.
- **The technical challenge is substantial: ~85% of cement emissions come from the calcination process or high-temperature heat sources.** Getting to net zero will require novel decarbonization measures, many of which do not exist yet at scale. A wide variety of approaches are emerging across different stages of technological and adoption readiness.
- **Government procurement drives ~50% of U.S. demand, giving the public sector an outsized role in accelerating decarbonization.** Yet the cement value chain structure complicates decarbonization efforts: cement is bought through multiple layers of intermediaries, challenging efforts to create a clear demand signal. Other features of the cement market further constrain decarbonization approaches.
- **Industry momentum has been slower to build in the U.S. than in other parts of the world, particularly Europe. However, activity is beginning to accelerate, especially in response to the Inflation Reduction Act (IRA).** Established cement companies have set decarbonization targets and are exploring options, a robust start-up ecosystem has emerged with 40+ companies developing novel cement products, and commercial-scale demonstrations of key technologies are planned for the mid- to late-2020s, facilitated by government support.

Section 2.a: Sector overview – Introduction to cement

Cement is the key ingredient in concrete, the most consumed human-made material on Earth, and is a vital upstream input for housing, built infrastructure, and a wide range of critical construction projects. [viii]

The market today faces challenges meeting intertwined climate and economic development goals. Producing the 4B+ tonnes of cement needed to meet global demand for concrete each year is associated with ~7–8% of annual CO_2 emissions. [ix, x, 10] Global consumption will grow further as developing countries continue to industrialize and urbanize, and cement will be a critical input for infrastructure projects needed as part of the global energy transition.[xi] Cement emissions cannot grow linearly if the sector is to remain on track for decarbonization. In the U.S., the cement sector accounts for ~70M tonnes of annual emissions, ~1–2% of total CO_2 emissions, and ~8% of emissions in the industrial sectors of focus under the Inflation Reduction Act.[xii]

Decarbonizing domestic production will be critical for achieving net zero in the U.S. and creates an opportunity for the U.S. to lead globally on innovation, commercialization, and export of the next generation of low-carbon cement technologies.

Section 2.a.i: Cement production process

Cement is a binder mixed with water and aggregates like sand and gravel to produce concrete. Portland cement, the most widely used type, was developed in the early 1800s and is a mixture of calcium silicates and other compounds derived from limestone and silica sources that hardens when it reacts with water. [xiii]

10 According to the U.S. Geological Survey, in 2022, China was the largest consumer of cement by far, accounting for 51% of the market. India was the second largest, with 8% of the market.

The key ingredient in Portland cement is clinker, a binder material made by sintering limestone and aluminosilicate materials like clay at high heat. Clinker production accounts for the vast majority of emissions in the overall process.

Cement production follows a basic three-step model (Figure 2.1): [xiv]

- **Extraction and preparation of raw materials**. Limestone and other raw materials like clay are quarried, crushed, milled, mixed, and ground to a sufficiently small size.
- **Production of clinker**. The limestone and raw materials mixture is typically preheated in a multi-stage precalciner and fed into a massive cylindrical rotary kiln heated to ~1,400–1,450°C. Reactions in the kiln produce clinker.
- **Production of cement.** Clinker is cooled, ground to a fine powder, and mixed with gypsum, limestone, and potentially other additives in specific amounts (defined by standards) to form the final cement mix for sale.

85% percent of emissions come from clinker production and are intrinsic to the chemical process or related to the high heat at which it takes place (Figure 2.1): [11, xv]

- 51% of total emissions come from the calcination process used to make clinker, in which CO2 is produced as a byproduct of quicklime (CaO) extraction from limestone (calcium carbonate, $CaCO_3$) in the kiln.
- Another 34% of total emissions come from the fuels used to generate high heat at the kiln—plants typically use coal and coke today and increasingly burn natural gas and some wastes (e.g., tires). [xvi]

Figure 2.1. Cement production process

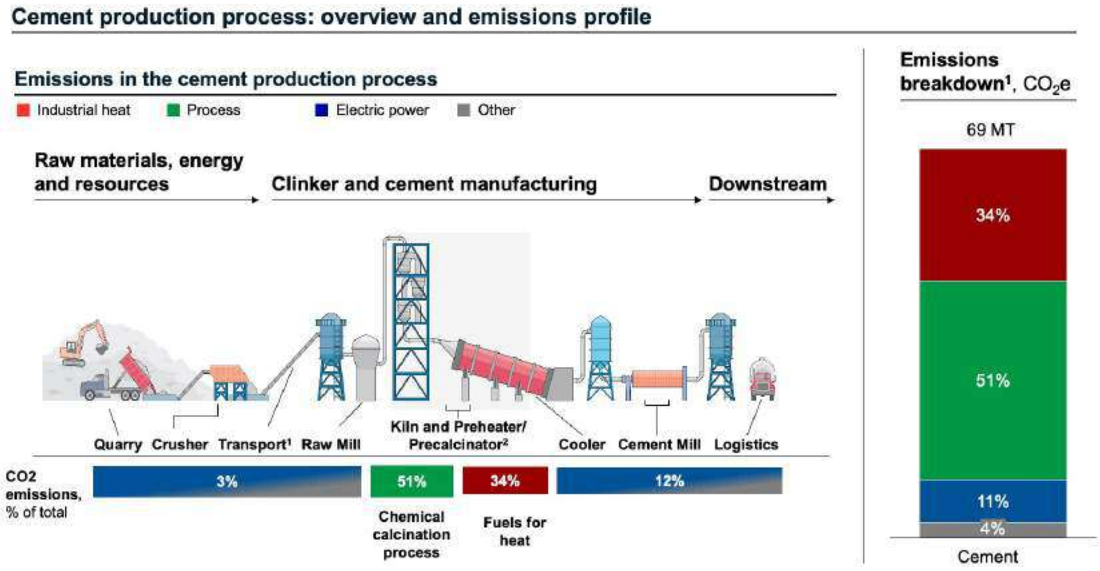


Figure 2.1. Overview of the cement production process with corresponding emissions by source. 85% of emissions come from clinker production in the preheater/precalciner and kiln, of which 51% are intrinsic to the chemical calcination process and 34% come from the combustion of fuels for heat.
Notes: 1. U.S. EPA. (2021). Facility Level GHG Emissions Data from Large Facilities [Data set]. https://ghgdata.epa.gov/ghgp/main.do?site_preference=normal. Visual from Czigler, Thomas, et al. (2020, May). "Laying the foundation for zero-carbon cement." McKinsey and Company. Laying the foundation for a zero-carbon cement industry | McKinsey.

11 These figures are drawn from EPA 2021 facility-level emissions data. Similar figures are given by 2015 U.S. Geological Survey energy-use data, which report 58% of emissions from the process and 42% from energy (of which 8% comes from electricity consumption and 34% from fuels). Hendrik G. van Oss (2020, Jan.). 2016 Minerals Yearbook: Cement. U.S. Geological Survey. https://d9-wret.s3-us-west2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2016-cement.pdf.

Section 2.a.ii: U.S. market context

The U.S. is the fourth largest market for cement in the world. The U.S. consumed ~120M tonnes and produced ~95M tonnes of cement in 2022, with total sales worth an estimated $14.6B and an average price of $130 per tonne. [xvii] Domestic production is forecast to grow by ~31% to 124M tonnes in 2050 (~1% CAGR from 2023–50). [xviii]

The U.S. also imports ~24M tonnes of cement annually. 38% percent of cement imports come from nearby suppliers in Canada and Mexico, but 62% comes from countries like Turkey and Greece, typically where suppliers with access to water transport can take advantage of the low freight cost to ship cement by boat and barge. [xix]

Section 2.a.iii: U.S. cement production footprint

Today, the U.S. has 98 total cement plants that must be decarbonized to achieve net zero in the sector—96 in 34 states and two in Puerto Rico**.** [xx] Just four states (Texas, Missouri, California, and Florida) account for ~43% of shipped cement. [xxi] Plants are sited close to population centers and the markets they serve to minimize transport costs.

U.S. cement plants, excluding capacity in Puerto Rico, collectively operate 120 kilns with a mean age of 36 years, but the facilities are not homogenous. About two-thirds of capacity is provided by larger, more modern kilns (with ~0.75–1.5 MTPA of clinker output), while the remaining third is from smaller, older kilns (Figure 2.2). [xxii] This pattern reflects a decades-long trend of consolidating production in fewer, larger facilities. [xxiii] The last major wave of investment occurred from 2000–09 when 31 kilns representing ~41 MTPA of capacity were built or substantially overhauled (Figure 2.3), but the industry continues to invest in modernizing and expanding existing plants, as well as building new ones. [xxiv, xxv]

Figure 2.2: Current kiln footprint

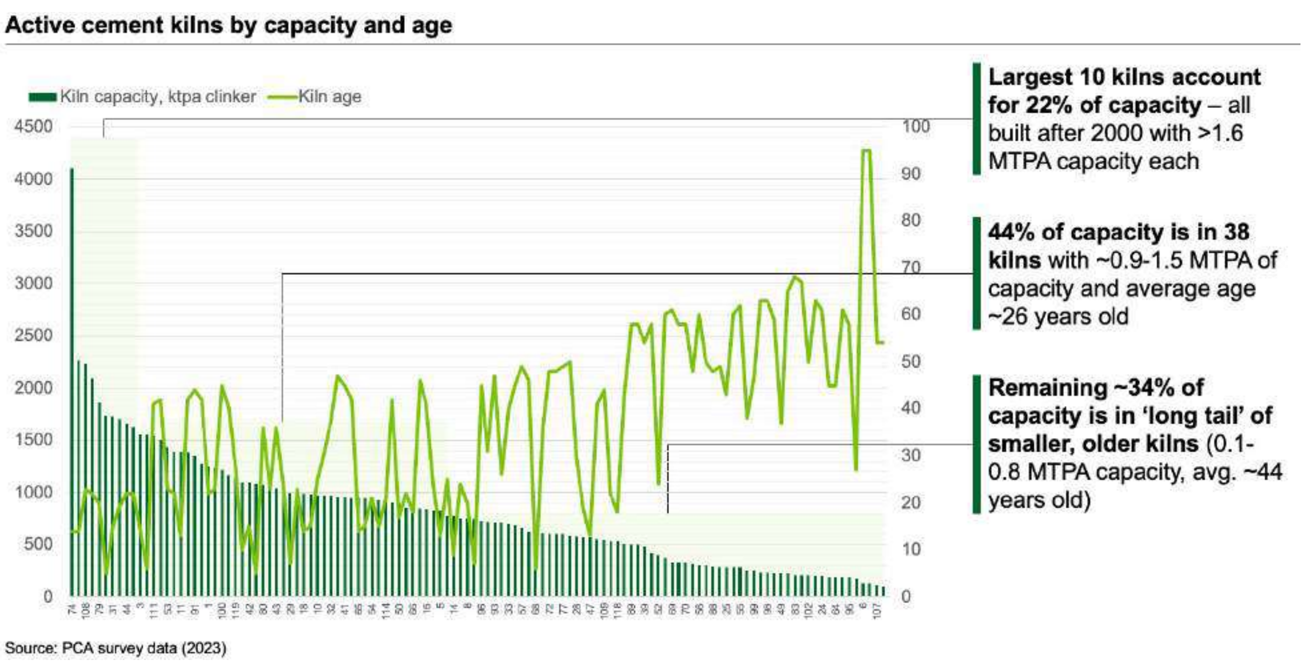


Figure 2.2. Current kiln footprint. X-axis shows each active cement kiln by capacity (in terms of clinker production) and age. 22% of capacity is concentrated in the largest 10 kilns, all built after 2000. Another 44% of capacity is in slightly older midsized kilns. The remaining 34% of capacity is in a 'long tail' of smaller, older kilns. Source: Portland Cement Association (2019, Dec. 31). U.S. Portland Cement Industry: Plant Information Summary.

Figure 2.3: Historical investment cycle for cement plants

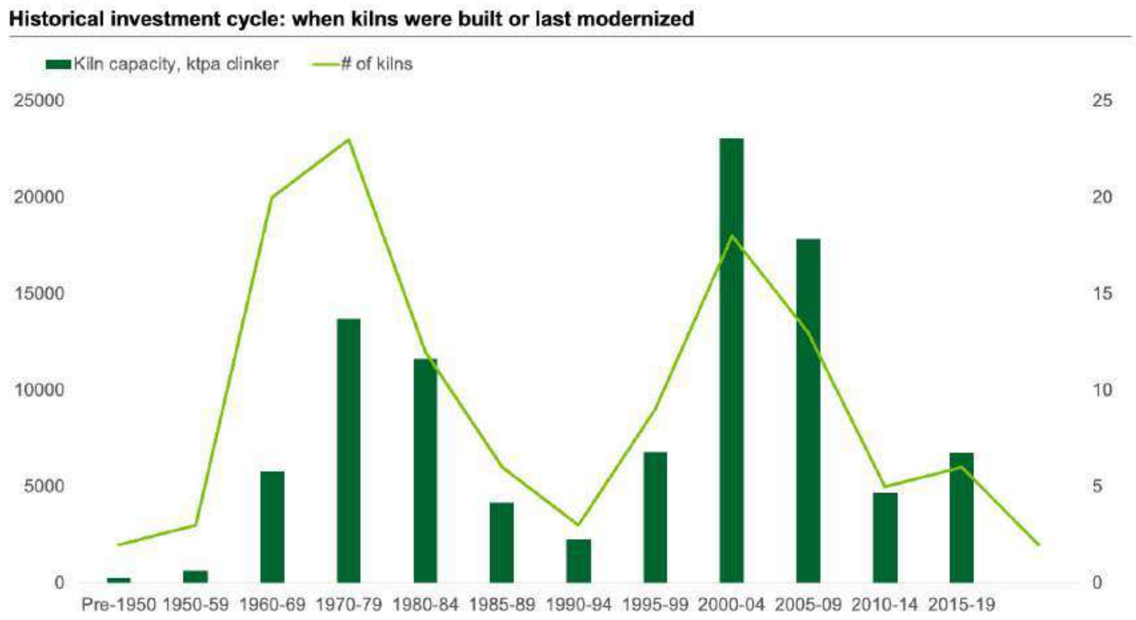


Figure 2.3. Historical investment cycle for cement plants. Number of kilns and capacity by period of construction or most recent modernization. The most recent surge in investment came in 2000–09 when 31 kilns representing ~41 MTPA of clinker-production capacity were built or modernized. Source: Portland Cement Association (2019, Dec. 31). U.S. Portland Cement Industry: Plant Information Summary.

Section 2.b: Technology landscape

Because emissions intrinsic to the production process or associated with high industrial heat drive ~85% of emissions, decarbonizing cement production will require innovative and sector-specific approaches, potentially including fundamental changes to the production process. A wide range of potential approaches are emerging, but they are at different stages of technological and adoption readiness (Figure 2.4).

Figure 2.4: Overview of representative approaches to cement decarbonization

NON-EXHAUSTIVE // REPRESENTATIVE MIX OF TECHNOLOGIES // FIGURES INTENDED TO BE BROADLY REPRESENTATIVE, NOT REFLECTIVE OF ANY INDIVIDUAL COMPANY OR PROPRIETARY TECHNOLOGY

High cost — Value accretive; Low — High

Emissions source	Potential approaches		Cost, $/t CO2	Cost, $/t cement	Unconstrained abatement potential,[5] (% to BAU)	ARL[6]	TRL[6]
Cross-cutting	Energy efficiency[1]		(35-40)	(0-5)	Up to 20%	5-9	9
	Clinker substitution	Portland limestone cement[2]	(75-80)	(5-10)	5-10%	7	7-9
		Fly ash blended cement[2]	(25-30)	(5-10)	30-50%	7	9
		Steel slag blended cement[2]	(15-20)	(5-10)	30-50%	7	9
		Natural pozzolans blended cement[2]	(70-75)	(15-20)	30-50%	2	7
		LC3 (Limestone Calcined Clay) blend[2]	(60-70)	(15-25)	30-50%	5	9
Heat	Alternative fuels	Biomass fuel[3]	30-35	0-5	1-8%	4	9
		Waste fuel[3]	(0-10)	(0-5)	1-4%	5	9
	Precalciner & kiln electrification		Emerging technologies		Up to 35%	1	5-6
Process	CCUS (with 45Q)[4]		35-75	25-55	85-99%	1	6-7.5
	Alternative production methods		Emerging technologies		25-100%	1	3-5
	Alternative binder chemistries				25-100%	1	3.5-9

Note: Approaches above are focused on primary production of cement. Additional approaches are available in downstream production of concrete (e.g., reduced cement consumption in concrete mixes, carbon curing of precast concrete products).

Figure 2.4. Overview of representative approaches to cement decarbonization. Not exhaustive—intended to illustrate the emerging mix of technologies and approaches. Not reflective of any individual company or proprietary technology. Approaches have different cost implications and are at different TRLs and ARLs. Energy efficiency, clinker substitution, and alternative fuel (waste and biomass) approaches are broadly at a high ARL and TRL today, with neutral to favorable economics and the potential to abate ~30–40% of emissions cumulatively (though all three areas also have opportunities for further R&D investment, including more novel substitute materials, expanded use of alternative fuels, and more dramatic efficiency measures). Getting to 100% abatement will require technologies at lower ARL and TRL and with more challenging economics like CCUS, alternative production methods, and alternative chemistries.
Notes: 1. A range of efficiency measures are available, but they are at different ARL and TRL today. Costs are estimated for measures that are deployable today, with more limited abatement potential. | 2. Clinker substitution economics estimated using blended cement composition ratios provided in Appendix A. | 3. Fuel abatement potential and economics estimated using fuel mixes and feedstock cost benchmarks provided in Appendix A. | 4. CCUS costs estimated using methodology discussed in Appendix B. Costs reported here are for CCS specifically and include $85/tonne 45Q tax credit. | 5. Unconstrained abatement potential is for a given tonne of cement produced, not estimated for the entire cement sector. It is estimated for each approach in isolation (i.e., not tied to a specific decarbonization pathway or sequence of approaches). | 6. ARL and TRL figures are representative estimates based on DOE and expert input. They do not reflect an assessment of any specific individual company or proprietary technology and should not be interpreted as such. For electrification, high end of range reflects potential for precalciner electrification, which is less technically challenging than kiln electrification because of the lower temperatures required.

The decarbonization approaches discussed in this report tie to the DOE's Industrial Decarbonization Roadmap pillars and prior Liftoff reports. Energy efficiency, industrial electrification, and carbon management have separate pillars in the Roadmap, although the Roadmap includes clinker substitution under energy efficiency. Alternative fuels, hydrogen, and several alternative production methods are counted in the Low Carbon Fuels, Feedstocks, and Energy Sources pillar.

Approaches can be broken out at a high level by emissions source.

Section 2.b.i: Cross-cutting measures

A set of cross-cutting measures can reduce overall emissions by reducing consumption of emissions-intensive clinker in cement mixes ("clinker substitution") and improving the efficiency of the production process.

Clinker substitution reduces the emissions associated with a given volume of cement by replacing part of the clinker in the cement mix with materials with lower embodied carbon. Clinker substitution measures are broadly at high TRLs and high ARLs today, with favorable economics: [12]

12 Detailed assumptions of cost analysis are provided in Appendix A.

- Traditional substitutes (e.g., ground limestone, fly ash, steel slag) are already commercially used, albeit at a limited but growing scale.
- Emerging substitutes (e.g., calcined clays, natural pozzolans) have demonstrated technical viability but are still deployed at a limited scale.
- More novel substitutes (e.g., engineered SCMs) are promising longer-term technologies but are in different states of readiness and will require continued R&D investment.

Different proportions of the clinker in a cement mix can be substituted with various materials to produce different lower-carbon blends. Cement blends currently in widespread use, like Portland Limestone Cements (PLCs), substitute up to 10–15% of clinker with materials such as ground limestone, driving 5–10% emissions reductions. [xxvi] More ambitious approaches, like ternary blends and calcined clay cements (e.g., Limestone Calcined Clay Cement, "LC3"), allow for substitution of ~30–50% of clinker in a cement mix by weight, driving emissions reductions of ~30–50%. Blends with steeper clinker substitution are technically proven and have strong economics but remain in limited use today.[xxvii, xxviii, xxix] Potential for scale-up of clinker substitution is discussed in greater detail in Section 3.a.

This report focuses on the primary production of cement, but the industry can further cut emissions by reducing material consumption downstream in the value chain. By reducing cement content in concrete and concrete use in construction, the broader construction sector can further reduce overall clinker consumption, compounding the decarbonization effects of clinker substitution in cement. [xxx]

Efficiency measures at the cement plant offer additional opportunities to reduce emissions by reducing energy consumption throughout production. A range of high-TRL and economically favorable efficiency measures are available. [xxxi] Modeling for this report considers 24 potential measures that could be adopted by a representative plant with neutral to positive economics, including process control, more efficient internal transport systems, high-efficiency coolers and grinders, and high-efficiency motors and fans (the full list is provided in the appendix). [xxxii] Other efficiency measures are at lower TRL and ARL and are farther from deployment readiness.

Section 2.b.ii: Heat measures

For heat-related emissions, alternative fuels like wastes and biomass are technologically and commercially mature today, while clean hydrogen, electrification, and other industrial heating alternatives remain further from deployment readiness: [13, xxxiii, xxxiv, xxxv]

- **Waste fuels and biomass** are technologically mature (some wastes like tires are already used as fuel for kilns today) and can generally be deployed without significant cost impact (potentially around -$1 to $1 of impact per tonne of cement in the absence of policy or other market incentives), but abatement potential is limited and deployment comes with supply and environmental constraints (discussed in Section 3.a).
- **Precalciner and kiln electrification** remain technologically nascent and have uncertain but likely challenging economics because of their high energy requirement and associated costs, particularly for high-heat applications like cement kilns.[xxxvi] Precalciner electrification could be closer to viability because of the lower heat required.
- **Clean hydrogen** is more challenging economically and is not currently on track to see significant uptake in the near term given available alternatives. Clean hydrogen can likely be used as up to ~5-20% of the fuel mix without a significant overhaul of plant infrastructure, but securing clean hydrogen at sufficiently low cost to compete with existing fuels is likely to be challenging. Even with subsidized production from the 45V tax credit, clean hydrogen may be prohibitively expensive for most cement

13 Detailed assumptions of cost analysis are provided in Appendix A.

plants, especially if significant investment in transportation and storage infrastructure is required. The available supply of clean hydrogen may also go first to sectors with higher willingness to pay, such as heavy-duty transportation.[xxxvii] Using hydrogen at higher rates in the fuel mix (e.g., up to 100%, consistent with complete decarbonization of kiln heat) will likely require more fundamental reconfiguration of existing plants or greenfield plant construction, with substantial associated CAPEX and opportunity cost from downtime. [14, 15, xxxviii]

- **Alternative industrial heating techniques** like thermal energy storage could also have applications for cement (discussed in detail in the Pathway to Commercial Liftoff: Industrial Decarbonization report), but these techniques similarly remain at early stages of technological and economic maturity. [xxxix, xl] See the Industrial Decarbonization report for a more detailed economics discussion.

Section 2.b.iii: Process measures

There are limited options to address emissions from calcination, and they are typically at lower levels of technological maturity and adoption readiness: [16]

- **Alternative production methods** for traditional cement products (e.g., alternative noncarbonate feedstocks, electrochemical production methods, and other alternatives to traditional rotary kiln plants) remain at the pre-commercial pilot or pre-pilot stage, and deployment economics and market accessibility remain unclear. [xli] Their potential pathway to commercial-scale deployment is considered in Section 3.c.

- **Alternative binder chemistries** shift away from traditional Portland-type cement clinker entirely. Alternative chemistries include belite, sulphoaluminate, and "MOMS" (magnesium oxide derived from magnesium silicates) clinkers and other engineered materials. Some materials are commercially available today at a small scale, but many remain far from technological maturity and are generally far from broad market adoption. [xlii] Their potential pathway to commercial-scale deployment is considered in Section 3D.

- **Carbon capture, utilization, and sequestration (CCUS)** may be employed to address emissions that cannot otherwise be cost-effectively abated from process (and potentially heat).[17] There are multiple potential approaches to carbon capture for cement plants. Post-combustion amine-solvent capture technology is at higher TRL today. However, the low CO2 concentration in post-combustion streams results in high CAPEX and OPEX that, when combined with the cost of CO2 transportation and storage infrastructure, drive extremely high costs (potentially ~$35–75 per tonne of CO2 including the 45Q tax credit, ~$120–160 per tonne without it). [18] Emerging technologies (e.g., capture with oxyfuel combustion, calcium looping, methods for capturing just the purer stream of process emissions) could have significant technical and economic advantages in the longer term but are at much lower TRLs today. [xliii, xliv, xlv, xlvi, xlvii]

14 The U.S. National Clean Hydrogen Strategy and Roadmap sees cement production as a "Third Wave" application for hydrogen that will become economically competitive "as clean hydrogen production scales significantly and as costs decline and infrastructure becomes available." U.S. Department of Energy (2023). U.S. National Clean Hydrogen Strategy and Roadmap. https://www.hydrogen.energy.gov/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf.

15 Use of clean hydrogen may come with public and energy and environmental justice concerns that projects will have to address. Because hydrogen is currently positioned to play a more limited role in decarbonization of cement, justice implications of hydrogen projects are not considered extensively in this report, but detailed discussion can be found in the Pathway to Commercial Liftoff: Industrial Decarbonization and Pathway to Commercial Liftoff: Chemicals & refining reports.

16 Detailed assumptions of cost analysis are provided in Appendix A.

17 This report typically refers to "Carbon Capture, Utilization, and Sequestration" (CCUS) because of the significant potential for carbon utilization approaches in cement and construction materials. Where only sequestration is considered, "CCS" is used. Where only utilization is considered, "CCU" is used.

18 Cost estimates are based on NETL 2023 modeling for 95% capture at a preheater/precalciner kiln fueled with coal and coke, using CANSOLV amine-based post-combustion system. Capital costs are adjusted to reflect a 12-year payback period, consistent with what investors have said they would be willing to underwrite, using capital recovery factors from the Energy Futures Initiative. Transportation and storage costs of ~$10–40 per tonne of CO2 are assumed, consistent with the representative figures in the Carbon Management Liftoff report. The specific methodology is provided in Appendix B. Hughes, Sydney, and Patricia Cvetic. (2023, Mar.). Analysis of Carbon Capture Retrofits for Cement Plants. NETL. Microsoft Word - 17-4-1-2_Cement Plant Retrofit Capture_DFR_Rev7.docx (doe.gov). Brown, Jeffrey D., et al. (2023, Feb.). Turning CCS projects in heavy industry and power into blue chip financial investments. Energy Futures Initiative. EFI - CCS Report (energyfuturesinitiative.org).

Section 2.b.iv: Future technology landscape

To capitalize on opportunities for short and medium-term emissions reductions, it will be critical to improve the adoption readiness of the large number of technologies at high TRL but low ARL, especially the next generation of clinker-substitution and fuel-switching measures. But these measures will not be enough. Roughly 30-40% of emissions are addressable through currently deployable technologies, but full decarbonization of the sector will hinge on rapidly getting nascent technologies to technological maturity and bringing them into the market at scale.

Section 2.c: Market context: Structure, economics, and implications for deployment

The market context shapes the potential for deployment and eventual Liftoff of low-carbon cement technologies. The cement market has unique structural and economic attributes that create opportunities for and constraints on deployment.

Figure 2.5: Value chain map – cement, concrete, and construction

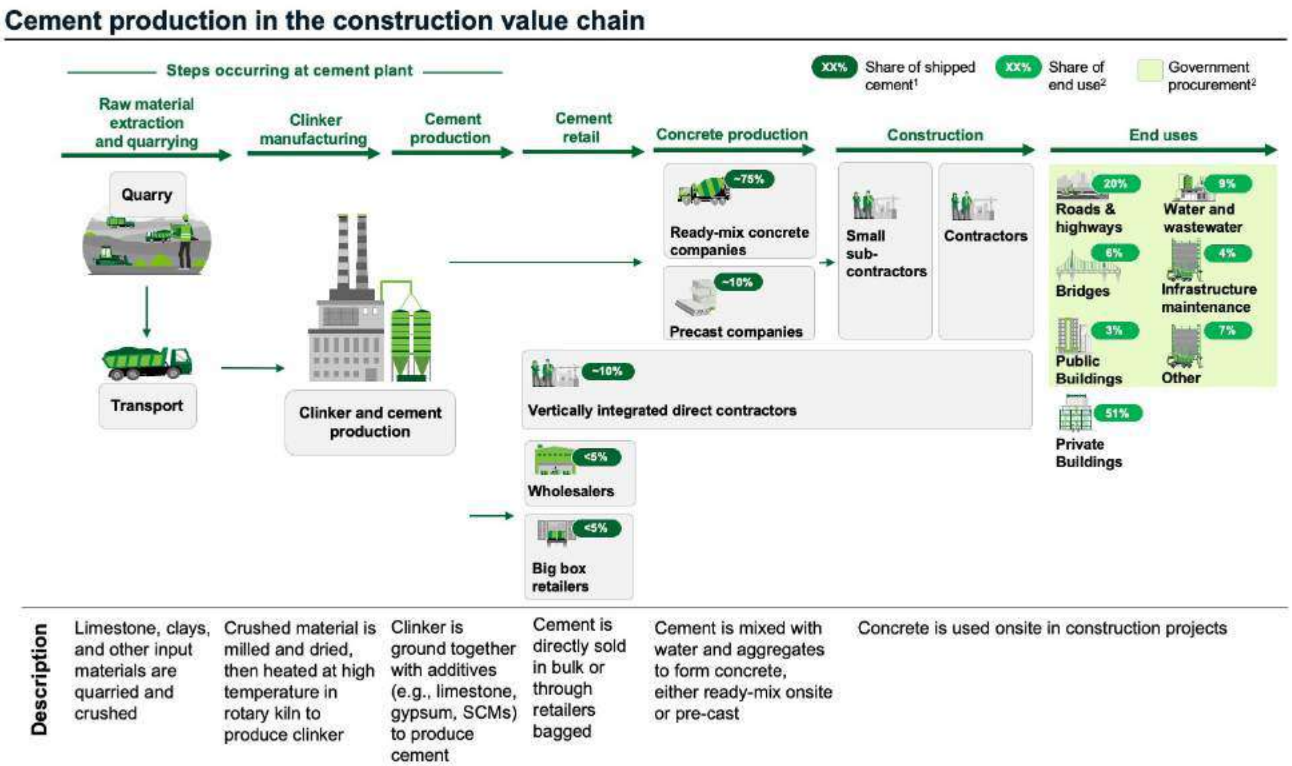


Figure 2.5. Overview of the cement-concrete-construction value chain. Cement production is upstream in the broader value chain. Government procurement accounts for roughly half of the end market for cement, but there are multiple layers of intermediaries (e.g., ready-mix companies, subcontractors, and construction contractors) between primary production and end uses. | 1. The share of shipped cement is estimated based on data from the Portland Cement Association's Survey of Portland Cement Consumption by User Group (2022). | 2. End-use share is estimated based on an analysis of data from the Portland Cement Association's U.S. Cement Industry Annual Yearbook (2022) by Breakthrough Energy Ventures.

Section 2.c.i: Cement market structure

Cement production is upstream in the broader construction value chain and represents a relatively small value pool within the construction industry. Total U.S. spending on cement was estimated at ~$14.6B in 2022, representing <1% of the ~$1.8T in total U.S. spending on construction, with cement being a typically small contributor to overall project costs (although this can vary based on project type). [xlviii, xlix]

The value chain is consolidated at either end but fragmented in the intermediate tiers. A few suppliers account for most production, and large buyers like government agencies for more than half of the demand, but between them are multiple layers of intermediaries:

- ***Supply side*. Production is increasingly consolidated in a small number of large companies, typically multinationals.** Twenty-four companies own all 96 active U.S. cement plants (excluding capacity in Puerto Rico), and the top 10 companies account for over 80% of installed production capacity. [l]
- ***Demand side.* Government procurement drives ~50% or more of U.S. cement consumption, giving the public sector an outsized role in shaping the market.** [19, li] Approximately 30% of total consumption—and two-thirds of government consumption—comes from roads, highways, bridges, and other infrastructure maintenance, with federal and state departments of transportation (DOTs) leading in setting requirements and allocating funding. [lii] The remaining third of government procurement is largely driven by water and wastewater infrastructure, utilities, and public buildings. The rest of the market is largely accounted for by private procurement for building construction (i.e., residential, commercial, and agricultural). [liii]
- ***Intermediaries.* There are multiple tiers of intermediaries in the value chain between primary production and end consumption, often with significant fragmentation**. Approximately 96% of all cement shipped goes through intermediaries (e.g., ready-mix concrete companies, concrete product manufacturers, contractors, and materials dealers) and there are typically multiple layers of ready-mix suppliers, subcontractors, and contractors between a cement plant and the end customer paying for a building or highway construction project. [liv] These intermediate tiers are often fragmented. For example, there are thousands of individual ready-mix concrete companies, which are often small businesses.

Section 2.c.ii: Product segmentation

Consumption of cement fits overwhelmingly into one of two concrete product segments, each with distinct attributes and requirements:

- **Ready-mix accounts for the largest share of the market but is a difficult segment for new materials to enter.** Approximately 70–75% of cement is used to make ready-mix concrete, which can be prepared onsite and used in various applications, including road paving and building construction. [lv] The ready-mix market has high barriers to entry, including more stringent product standards for structural applications like building construction. Additionally, because ready-mix concrete is prepared onsite in various environments and conditions, it is a challenging segment to break into for new cement products that may require tighter control of the concrete production process. However, because ready-mix accounts for such a large share of the market, deep decarbonization of the sector will require low-carbon technologies compatible with ready-mix applications.
- **Pre-cast is a smaller share of the overall market but can offer an initial foothold for new players.** Approximately 10–15% of cement is used in pre-cast applications where concrete is mixed,

19 ~49% before the Bipartisan Infrastructure Law and Inflation Reduction Act, which are assumed to increase the share of cement consumption driven by government procurement.

cast in a mold, and "cured" in a controlled environment before installation at a construction site. [lvi] Pre-cast products offer concrete suppliers more control over the production process and can be more amenable to new products, often providing an initial market niche.

The remaining ~10–20% of cement consumption is accounted for by bagged cement and specialty products.

Section 2.c.iii: Baseline economics

The baseline economics of cement production define the shape of the market. Four key factors are particularly important: [lvii]

- **High CAPEX and limited financing options for projects.** A new U.S. cement plant at 1+ MTPA scale can require $0.5–1.0B in CAPEX. [20] Major investments are typically financed on the balance sheet, either from existing assets and cash flow or by using traditional corporate finance: cement companies can have a high cost of capital due to their smaller size and the perceived risk of a merchant business model. [21] There is limited use of project finance for cement in the U.S. today; in conversations with numerous investors and large cement companies, no recent instance could be identified in which a project finance model was used. Moreover, large investment firms often have limited experience with cement projects and may not have analysts focused on cement companies, given their limited market capitalization. [lviii]

- **Long asset lives.** Facilities are expected to have asset lives of ~30–50+ years, with high CAPEX amortized over this extended period. [lix] In the current industrial base, 48 operational kilns were built before 1980; the oldest was built in 1928. [lx] Early retirement of plants represents a significant cost to cement companies.

- **High opportunity cost of downtime.** Similarly, plants are expected to operate with minimal downtime. They are taken offline for short periods on a roughly annual basis to be relined, but major overhauls are typically done on a decadal or multi-decadal timeline to minimize opportunity cost. Based on public data, one year of downtime at a representative 1-1.5 MTPA capacity cement plant could represent ~$100–200M of opportunity cost. [22] Interventions (e.g., retrofits with new technologies) that come with significant plant downtime will thus incur substantial additional costs.

- **OPEX driven by fuel and freight costs.** Production is optimized to minimize fuel costs, and any intervention that increases the cost of fuel is likely to have an outsized impact on overall production cost and margin. Both input materials and the finished product are also heavy and expensive to transport by land, and interventions that require longer-distance shipping of materials can quickly and significantly impact cost and margin.

Section 2.c.iv: Market attributes and implications for deployment

Four market attributes, shaped by the underlying economic dynamics of the sector, define the deployment model and viable business models for new technologies:

- **Regional fragmentation.** Because of high freight costs, the cement market is regionally fragmented. Cement is heavy. Freight cost typically makes it prohibitively expensive to ship cement far, and U.S. plants have limited access to lower-cost rail or waterborne transportation—71% of cement is shipped

20 Based on conversations with industry subject matter experts and large cement companies. Also see, e.g., Heidelberg's recent $600M investment in a new plant in Mitchell, IN. Heidelberg Materials (n.d.). "Mitchell K4." https://www.heidelbergmaterials.us/sites/mitchell.

21 This may be less relevant for large, integrated materials companies, typically international conglomerates, that have amassed a growing share of the U.S. cement market through recent acquisitions.

22 Assuming 1-1.5 MTPA of cement output at the $130/tonne average price estimated in 2022 by U.S. Geological Survey.

from the plant gate by truck, 19% by rail, and 10% by barge and boat. [lxi, 23] Plants are built close to customers and serve a local market, with their ability to realize economies of scale capped by the size of that serviceable demand pool. Decarbonization solutions must accordingly be tailorable to the unique conditions at each plant site.

- **Lack of long-term offtake agreements.** Cement procurement is typically a “handshake business” without long-term offtake. The ready-mix companies and contractors that are typically the immediate customers for cement producers buy on an as-needed basis for their construction jobs. Customers are reluctant to commit to longer-term offtake because of uncertainty about long-term demand amidst boom-and-bust construction market cycles. This model leaves cement plants with significant merchant risk and complicates efforts to create a credible long-term demand signal for the scale-up of new technologies.
- **Rigid industry standards and specifications tightly govern the deployment of cement and concrete**. An end user like a developer or construction company will set requirements for performance (e.g., consistency, strength, air content) and exposure conditions (e.g., proximity to water, exposure to chemicals), dictating the composition of the concrete mix and the type of cement that must be used. Industry associations like the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO, focused specifically on roads and highways) provide voluntary standards almost universally adhered to regarding defined cement types and compositions. These standards can either be prescriptive, detailing the specific composition of a cement blend, or performance-based, which require materials to meet certain performance benchmarks while offering more flexibility concerning precise composition. Large, high-profile customers like state DOTs play a major role in setting norms for an entire market and may do their own testing of materials. Specifications set by state DOTs are often taken as the authoritative model for other customers. To enter the market at scale, cement products must be compatible with standards and usually accepted by trusted authorities.
- **Risk-averse customers.** Customers are risk-averse and generally have a long adoption cycle for new approaches and products. Customers like ready-mix companies, contractors, and engineers are highly sensitive to the potential risks of adopting new technologies, which can range from cost/schedule overruns to life-safety risks. Particularly for structural use cases (e.g., construction of high-rise buildings, bridges, and other critical infrastructure), preventing performance issues is of paramount importance for cement and concrete users along the entire value chain (discussed in additional detail in Chapter 4).

Section 2.d: U.S. industry momentum

Over the last two decades, the U.S. has reduced the emissions intensity of cement, but further reductions are required to hit climate and decarbonization targets. Since 1995, the U.S. cement industry has reduced its emissions intensity per tonne of cement by ~10%, mostly by finding efficiencies in production and phasing in natural gas instead of coal and coke. [lxii] As of 2020, 92% of U.S. plants, accounting for 98% of production, were using the less energy-intensive dry kiln production method. [lxiii] About 73% of U.S. cement plants currently use some share of alternative fuels: the share of energy consumption accounted for by alternative fuels increased from 2% in 1996 to 16% in 2019. Since 1996, the share of thermal energy from coal and coke has fallen from 74% to 59%, while the share of natural gas has increased from 7% to 25%. [lxiv] More recently, the industry has phased in using Portland Limestone Cement (PLC), a blended cement that substitutes ground limestone for up to 15% of the mix to reduce clinker factor, typically yielding ~8% reduction in emissions intensity (see the following case study). However, the U.S. cement industry still has significant progress to make to reach net-zero targets.

23 ~97% of cement is shipped the ‘last mile’ to customers by truck. The phenomenon comes from cement that is shipped first by rail or water from the plant to a central terminal, then transported by truck to customers.

Today, the U.S. lags behind Europe and other parts of the world in adopting low-carbon approaches. The EU uses alternative fuels for ~50% of primary energy consumption in cement, compared to just ~15% in the U.S.[lxv] This higher share is enabled in large part by the comparatively high cost to landfill waste in the EU, which creates a strong economic case for the use of waste-based fuels.[lxvi]

The first commercial-scale demonstrations of deep decarbonization technologies are also largely happening outside of the U.S.[lxvii] Heidelberg Materials has broken ground on the first commercial-scale cement-carbon-capture facility at their Brevik plant in Norway and plans to begin operations by 2024.[lxviii] As of 2022, GCCA has identified more than 30 other projects worldwide, most concentrated in Europe.[lxix] Construction of the first commercial-scale cement CCUS deployment in North America is underway at Heidelberg's plant in Edmonton, Alberta, Canada.[lxx] Government support has been critical for project viability so far. For example, the Edmonton project has moved forward with significant support from the Canadian government, including direct financial support and carbon pricing.[lxxi, lxxii]

Though initial momentum has built overseas, interest in U.S. deployments is growing quickly post-IRA, and the U.S. could recapture global leadership with bold action.

Established cement companies are exploring the feasibility of deploying new technologies, including CCUS, at existing plants and more aggressive clinker substitution approaches like calcined clay cements. Clean Air Task Force counts five U.S.-based CCUS projects in the cement sector, all in early stages.[lxxiii] These projects include (1) a partnership between Holcim, Svante, Occidental, and Total Energies to explore the feasibility of carbon capture and sequestration at Holcim's Florence, CO plant, (2) DOE-funded feasibility and FEED studies for deployments at Holcim's Ste. Genevieve plant in Bloomsdale, MO, (3) CEMEX's Balcones, LA, plant (4) Heidelberg's new Mitchell, IN plant, and (5) a partnership between Heidelberg and the start-up Fortera to produce a supplementary cementitious material using captured CO2 from Heidelberg's Shasta, CA, cement plant.[lxxiv, lxxv, lxxvi, lxxvii, lxxviii]

Beyond incumbents, a robust startup ecosystem of 40+ new companies has developed to bring new production methods and novel products to market along the entire value chain.[lxxix]

Case study: Portland Limestone Cement (PLC) rollout – A model for adoption of low-carbon cement blends

The large-scale adoption of Portland Limestone Cements (PLCs) has been one of the most significant early steps toward cement decarbonization in the U.S. PLC blends replace up to 15% (typically ~10–11%) of clinker content with ground, uncalcined limestone and can achieve an ~8% average reduction in emissions compared to traditional Portland cement.[lxxx] PLCs were approved under the widely used ASTM C595 standard in 2012 and today account for roughly one-third of cement shipped in the U.S.

Figure 2.6: U.S. rollout of Portland Limestone Cements

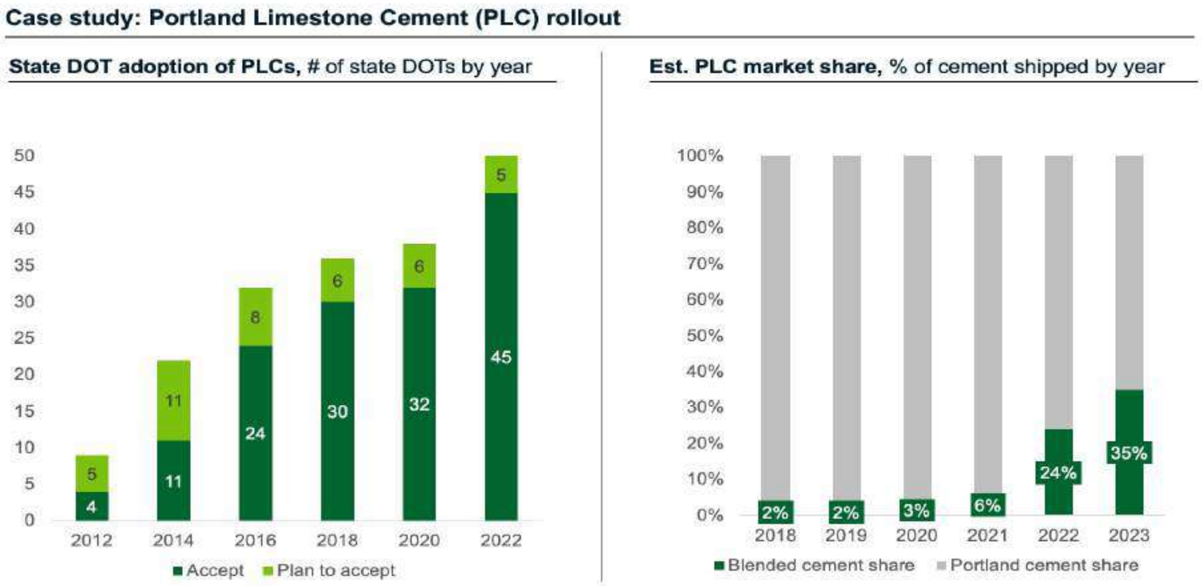


Figure 2.6. Key leading and lagging indicators from the PLC rollout: adoption by state DOTs and estimated market share. It took ten years for all 50 state DOTs to accept or have a plan to accept PLCs, and broader market uptake lagged state DOT uptake by several years. Source: State DOT adoption figures by year from Portland Cement Association. The established PLC market share is based on the share of blended cements reported in U.S. Geological Survey Mineral Industry Surveys. 2023 share estimated based on data through May 2023. The blended cements category includes other kinds of blended cement besides PLCs, but USGS estimates that 96% of total blended tonneage was driven by PLCs in 2023.

The PLC rollout provides valuable lessons for how other decarbonization approaches, particularly more aggressive clinker substitution in blended cements, could get to scale this decade:

- **Without intervention, the industry can have a 10+ year adoption cycle even for blends with well-established track records and a strong economic case—a timeline incompatible with rapid deployment**. Clinker substitution with ground limestone had a long track record and a strong value proposition. Cements with limestone content have been used in Europe and other countries since the 1960s, and blending limestone into Portland cement has been allowed under Canadian standards since 1983. In the U.S., up to 5% limestone has been used in Portland cements under ASTM C150 and AASHTO M85 since 2004 and 2007, respectively. [lxxxi] Because uncalcined limestone can be as much as ~$60 (~90%) cheaper per tonne than clinker, PLC blends also have a strong economic case, potentially enabling ~$5–10 of additional value capture per tonne of cement compared to OPC. [lxxxii] Yet it still took more than a decade after approval under industry standards for PLC to achieve substantial market share in the U.S.

- **As trusted first movers, state DOTs play a critical role in unlocking adoption by the wider market, but it can take ~5–10 years to reach a critical mass for adopting new materials.** Although ~5–10 first-mover states adopted PLCs within 1–2 years of initial acceptance under ASTM C595 in 2012, it took ~5 years for half and ~10 years for all 50 state DOTs to accept PLCs in their specifications. [lxxxiii]

- **Once tipping points are hit, however, market share can grow rapidly, potentially doubling year-over-year.** Even after most state DOTs had adopted PLCs, market share remained relatively stable at ~2–3% until 2021, when it began to grow rapidly, reaching ~35% of the market by 2023 (CAGR of 127% from 2020–23). [24]

The PLC rollout shows that rapid adoption of new lower-carbon cement blends is possible, but key barriers must be overcome to scale more aggressive clinker substitution methods (discussed in detail in Chapter 4).

24 Based on blended cement share of total shipped volume reported by the U.S. Geological Survey. USGS defines blended cements as products brought to market under ASTM C595, which will include PLC in addition to Portland-pozzolan and Portland blast-furnace slag cements.

Chapter 3: Pathway to commercial Liftoff

Key takeaways

- **Technologies could follow four distinct 'tracks' to commercial Liftoff** (outlined in Section 3.a.i below). In the short term, currently deployable measures could abate ~30% of emissions while delivering $1B+ in savings for industry by the early 2030s. In the longer term, achieving net zero by 2050 will require scaling technologies at lower TRL/ARL and with more challenging economics (CCUS, alternative production methods, and alternative binder chemistries).
- **Demand for low-carbon products will be the engine for Liftoff for all technologies.** Government procurement (state and federal) can play a decisive role in creating a strong demand signal for low-carbon cement.
- **The U.S. is positioned to lead internationally on decarbonizing cement production.** The U.S. can pioneer key technologies domestically, particularly low-cost CCUS and alternative production methods, then export them abroad to accelerate decarbonization of the ~7-8% of global CO_2 emissions driven by cement.
- **Scale-up will have to account thoughtfully for broader community impacts**. Scaling low-carbon cement technologies comes with powerful opportunities to benefit the economies, environmental quality, and health of fence-line communities, but some risks and concerns will also need to be addressed.

Figure 3.1: Pathway to Commercial Liftoff

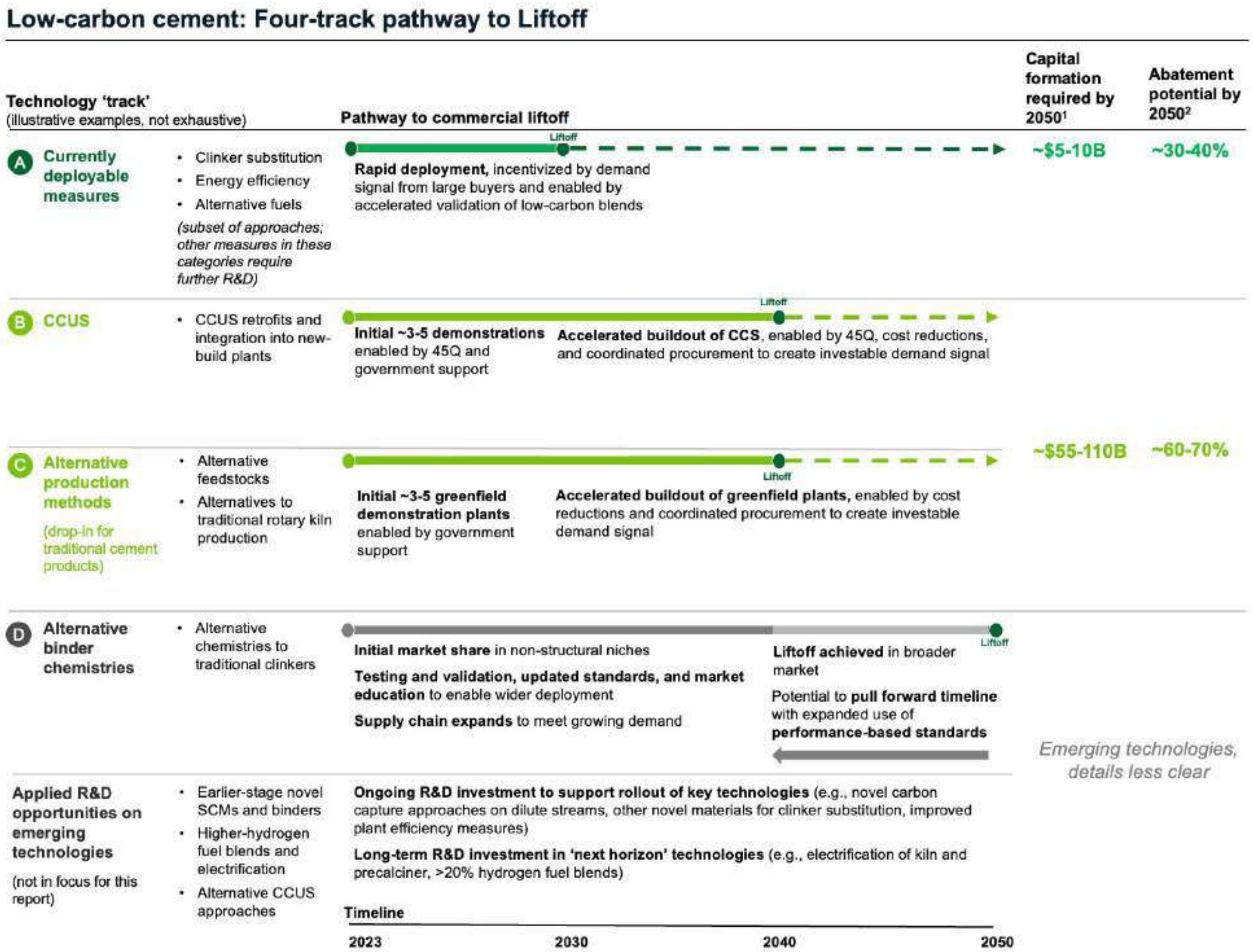


Figure 3.1: Liftoff pathway for the cement sector is split across technologies with varying TRLs/ARLs and distinct economic, market, and policy constraints and enablers. Four parallel 'tracks' are outlined for different technology types. Other technologies are on a longer timeline and require continuing R&D investment to achieve demonstration stage and deployment readiness.
Notes: 1. Capital formation opportunity was estimated according to methodology detailed in Appendix C (based on estimated CAPEX requirement to scale both currently deployable measures and CCUS or alternative production methods across the entire footprint of U.S. cement plants). 2. Abatement potential was estimated using methodology detailed in Appendix A (assuming the first 30–40% of emissions can be abated by a deployment-ready subset of clinker substitution, alternative fuels, and efficiency measures, with the remaining 60–70% addressed by CCUS and alternative production methods).

Section 3.a: Four-track pathway to Liftoff

Section 3.a.i: Four technology tracks

The pathways to commercial Liftoff for different low-carbon cement technologies will be shaped by their technology readiness, fundamental economics, and adoption cycles within the industry. This section identifies four parallel 'tracks' different technologies could follow to widespread commercial deployment and scale, all of which hinge on establishing a clear demand signal from end customers to cement producers:

A. **Currently deployable measures—clinker substitution, efficiency measures, and alternative fuels**—are compatible with existing standards, technologically ready, have a strong economic value proposition, and could achieve widespread adoption by the early 2030s. Aggressive deployment could drive ~30% emissions reduction by the early 2030s and ~40% by 2050.[25]

B. **CCUS** retrofits of existing plants and integration into new-build plants can scale from the 2030s, following initial demonstrations in the mid/late 2020s and supported by coordinated procurement, policy support, and cost reductions as deployments ramp.

C. **Alternative production methods** for traditional cement products can scale in the 2030s through greenfield plant deployments if they are demonstrated successfully and meet key performance and cost milestones in the late 2020s, with policy and demand support.

D. **Breakthrough alternative binder chemistries** can gain early footholds in niche, lower-risk applications, while passing through a longer-term adoption cycle to achieve full scale-up in the 2040s, with some potential to pull forward the timeline through broader adoption of performance-based standards.

Other emerging technologies are farther from commercialization and offer high-impact opportunities for applied R&D. These include transformative approaches like high-hydrogen fuel blends and kiln electrification, earlier-stage novel SCMs and binders and alternative approaches to carbon capture and utilization.

Section 3.a.ii: Demand as the engine for Liftoff

Establishing a strong demand signal out of coordinated procurement will be the first step for getting technologies to commercial Liftoff across all tracks. Credible demand for low-carbon cement products will incentivize companies to pursue decarbonization at the aggressive pace required to meet net-zero goals, unlock the business case for more expensive interventions, and allow capital-intensive projects to attract the investment they need. Coordinated procurement will need three components to shape the market effectively:

- **Procurement requirements for low-carbon products.** Large-scale buyers—particularly government agencies and the largest private-sector customers—are beginning to commit to procuring low-carbon materials at scale, and they can adopt requirements for their own purchases of these low-carbon materials (i.e., concretes using low-carbon cements) that are sufficiently aggressive to require suppliers to invest in new approaches. [lxxxiv, lxxxv] DOE's Industrial Decarbonization Roadmap projects that the U.S. cement industry could need to achieve a ~10% reduction in emissions by 2030, ~35% by 2035, and ~60% by 2040 to remain on track for net zero, and standards for low-carbon procurement could be correspondingly aggressive. [lxxxvi] Such requirements would also need to account for material performance to meet engineering requirements and to capture a material's full life cycle emissions impact.

  The federal government has already begun to set some requirements to these effects. EPA's Interim Determination for federal cement and concrete procurement requires materials purchased under IRA Sections 60503 and 60506 by GSA and DOT to be in the top 20% of the market based on emissions reduction, with adjustable requirements if materials are not available. [lxxxvii] GSA's low-carbon procurement pilot program sets specific emissions thresholds for cements and concretes. [lxxxviii]

- **Clear, credible quantification of embodied carbon.** Market actors in the public and private sectors can develop a shared set of credible metrics and standards for embodied carbon in cement and downstream products, supported by robust measurement and verification systems, data-sharing, and documentation (i.e., through standardized and widely available EPDs) to ensure purchased cement and concrete products meet low-carbon procurement standards (related challenges and potential solutions are considered in detail in Chapter 4). [lxxxix] EPA is currently leading an effort and providing grant funding to support improved market data for measurement, calculation, and verification of embodied carbon in materials, and future efforts can build on this foundation.[xc]

25 Based on modeling detailed in Appendix A.

- **Demand signal that reaches cement plants.** Large-scale buyers must develop ways to pass the demand signal for low-carbon cement through multiple layers of intermediaries in the value chain to cement plants. This could require more active management of construction supply chains and potentially using innovative contracting structures that allow for direct agreements between end customers and cement plants (related challenges and potential solutions are considered in detail in Chapter 4).

With their commanding share of the market and clear means of coordination, federal and state governments can play a particularly powerful role in implementing such a model.

To succeed in driving deep decarbonization, a coordinated procurement model must evolve to incentivize and economically enable ever-steeper reductions in embodied carbon. Initial investments to develop embodied carbon standards, the necessary data ecosystem and assessment methodologies, and deep supply-chain visibility will provide foundational capabilities for a long-term procurement regime. Longer term, large-scale buyers must raise standards for decarbonization and add new capabilities to support the deployment of technologies with more complex demand-side requirements.

The rest of this section considers how demand for low-carbon materials can pull technologies along each of the four tracks to Liftoff.

Section 3.a.iii: Commercial Liftoff by track

Track A: Currently deployable measures: Clinker substitution, efficiency measures, and alternative fuels

Key takeaways

- **Clinker substitution, efficiency measures, and alternative fuels are deployable today and could allow the industry to save ~$1B+ per year while abating ~30% of sector emissions by the early 2030s and ~40% by 2050.** Clinker substitution is the most powerful short-term lever, potentially abating ~25% of emissions and driving ~$5–20 of savings per tonne of cement.
- **Credible demand from large end customers, particularly requirements for low-carbon materials in project specifications, is needed to accelerate Liftoff** by incentivizing intermediaries in the value chain to use low-carbon cements and providing cement companies with the assurance that customers will buy low-carbon blends.

Clinker substitutes, efficiency measures, and alternative fuels are technologically proven, compliant with existing standards, and have strong economics today. Deployed aggressively, they could collectively abate ~30% of cement sector emissions and allow cement producers to capture an additional $1B+ of value per year by the early 2030s. With expanded deployment, they could abate ~40% of emissions by 2050. Each is considered in more detail below.

Clinker substitution

Clinker substitution has a strong positive economic case and will be the industry's most powerful abatement lever through the early 2030s. Deploying blended cements that are compliant with existing standards could yield an additional ~$1B of value per year industry-wide while abating ~20–25% of sector emissions by 2030. [26, 27]

Figure 3.2: Clinker substitutes – key attributes and economics

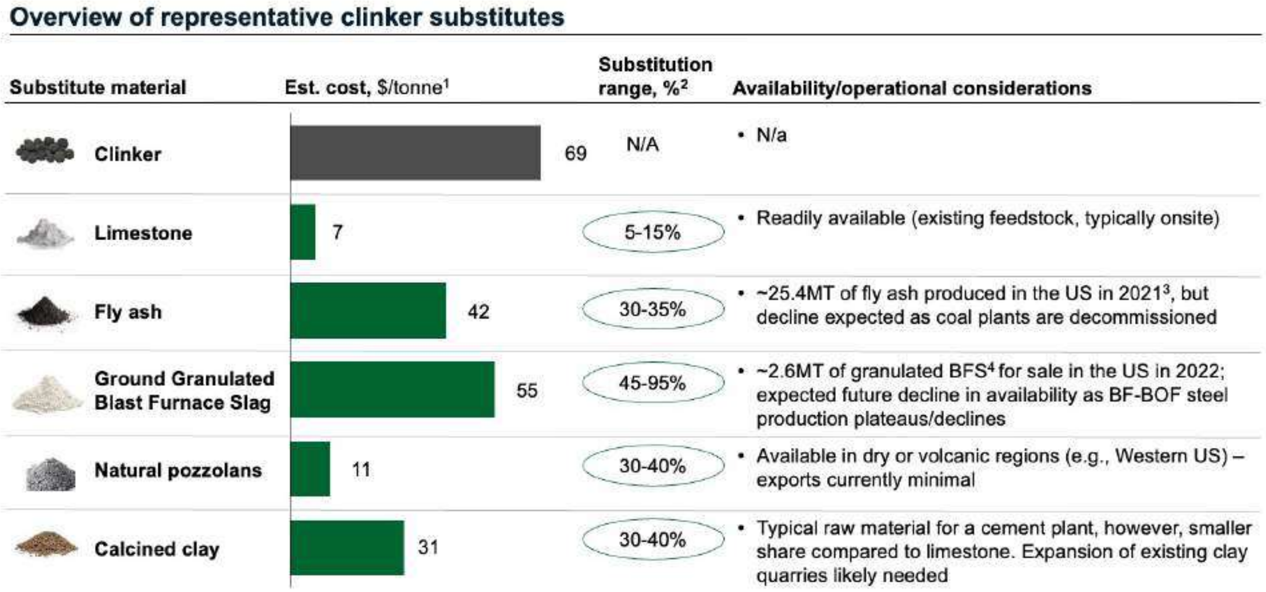


Figure 3.2: Overview of representative clinker substitutes with key attributes and economics. Clinker is energy-intensive and expensive to manufacture. Substitutes can be significantly cheaper per tonne, and substitution can thus drive significant reductions in cost. Materials can be substituted for ~5–15% of the mix by weight for limestone to up to 95% for slag. ~30–40% is more typical/feasible for most SCMs. Additional availability and operational considerations apply: fly ash and slag have limited supply; natural pozzolans are widely available in some regions; clays are already widely available at cement plants but may require expansion of existing quarries. Notes: 1. Cost for each substitute material is estimated on a per tonne basis using assumptions detailed in Appendix A. Clinker cost per tonne was estimated outside-in using representative fuel, energy, and material costs. | 2. High end of substitution range is given by ASTM C595. Increasing substitution past a certain level can change the viable end applications for a cement mix, such that the high end is not attainable in all use cases. Low end of substitution range reflects more common and feasible substitution levels based on expert input. | 3. Adams, Thomas H (2022). "Coal Ash Recycling Rate Increases Slightly in 2021; Use of Harvested Ash Grows Significantly." American Coal Ash Association. https://acaa-usa.org/wp-content/uploads/2022/12/News-Release-Coal-Ash-Production-and-Use-2021.pdf. | 4. U.S. Geological Survey (2021). Mineral Yearbook: Iron and Steel Slag. https://www.usgs.gov/centers/national-minerals-information-center/iron-and-steel-slag-statistics-and-information.

Most substitute materials are cheaper than clinker, making substitution favorable economically. Clinker can cost ~$60–70 per tonne with typical fuel and power costs, while ground limestone costs $5–10 per tonne, although it is capped at 15% of a mix by current standards. Traditional SCMs like fly ash and steel slag cost $40–60 per tonne, and emerging SCMs like natural pozzolans and calcined clays could cost $10–35

26 Detailed calculations and underlying analysis are provided in Appendix A. The aggressive deployment scenario assumes cement producers can reduce clinker factor industry-wide to ~65% by the early 2030s by scaling a mix of substitutes and deploying low-clinker cements like calcined clay cements and other ternary blends. It should be noted that this level of substitution is significantly higher than targets set in both PCA's decarbonization roadmap (85% clinker factor by 2030) and DOE's Industrial Decarbonization Roadmap (84% by 2030, 66% by 2050). 35% substitution by the early 2030s is an ambitious target intended to reflect a high-end estimate of what industry could potentially achieve, driven by the powerful economic incentive from substantial cost savings and enabled by concerted effort (detailed in this chapter and Chapter 4).
The representative modeling exercise assumes the following shares by mass of materials in total U.S. cement production: 65% clinker, 15% limestone, 9% calcined clay, 5% gypsum, 3% fly ash, 2% natural pozzolans, <1% GGBFS, <1% other (does not sum to 100% because of rounding). Exact composition could vary. The modeling exercise makes some arbitrary assumptions informed by conversations with the industry and practical limitations on deployment (discussed in Appendix A).

27 ~25% emissions reduction for this level of deployment is roughly consistent with an RMI analysis suggesting that full-scale deployment of SCMs in the U.S. could abate ~38% of cement emissions. Esau, Rebecca, and Audrey Rempher (2022). "Low-Carbon Concrete in the Northeastern United States." RMI. Low-Carbon Concrete in the Northeastern United States - RMI.

per tonne (Figure 3.2). Representative low-carbon blended cements could deliver ~$5–20 of savings per tonne compared to high-clinker cements currently in use (Figure 3.3). At a representative 1.5 MTPA cement plant, this would equal $10–30M in annual savings or NPV of $75–230M with a 20–year investment lifetime.

Figure 3.3: Low-carbon cement blends

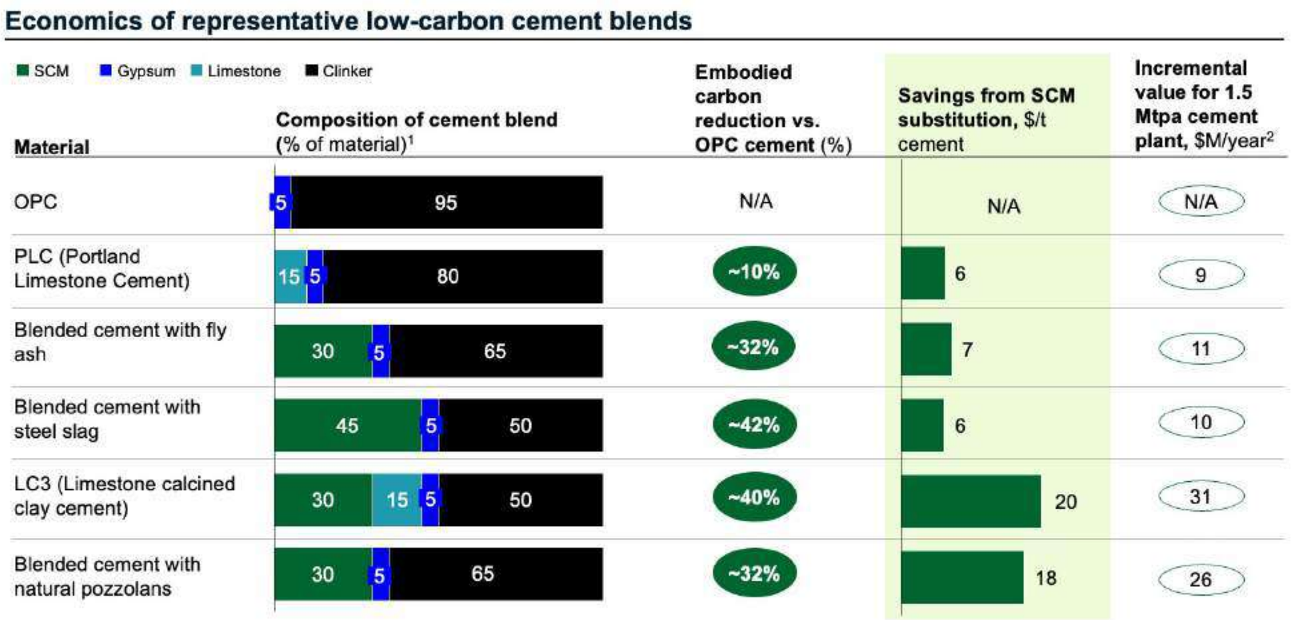


Figure 3.3: Representative low-carbon cement blends—composition, representative economics, and emissions reduction compared to ordinary Portland cement (OPC). Blends can achieve embodied carbon reductions of ~10% for PLCs to as much as ~40% for calcined clay and steel slag-based blends. Blends can also achieve savings of ~$5–20 per tonne, equivalent to ~$10–30M per year of additional value captured at a representative 1.5 MTPA cement plant. Detailed modeling assumptions are in Appendix A.
Notes: 1. ASTM C595 range; exact ratio chosen based on most likely given industry implementation/feasibility in the U.S. from conversations with industry experts. | 2. Based on a cement plant with 1.5MT of capacity per year.

While deployment costs will vary by site, the economics of clinker substitution are expected to be favorable under various circumstances. Plants must have a nearby source of substitute materials and may incur additional costs to make that source usable (e.g., investment to expand existing or develop new mines or quarries, investment in building out logistics infrastructure, and additional operating costs from transporting heavy materials). Public estimates suggest cement plants could produce calcined clay blends like LC3 with ~$15M of CAPEX investment, but conversations with industry suggest that some projects could require closer to $50–200M, with the discrepancy driven by the potential need to build new silos for material storage (at a cost of ~$50M each). [xci] Yet even if significantly higher CAPEX (e.g., $50–200M for new silos, storage facilities, and quarry redevelopment) and OPEX (e.g., from long-distance transportation of materials) are assumed, modeling suggests a wide range of projects could still be economically viable. [28]

The availability of raw materials constrains clinker substitution, but workarounds are available. Approximately 25 MT of fly ash and ~3 MT of steel slag suitable for cement production are available per

28 E.g., LC3 projects still deliver ~$5–20 of savings per tonne of cement even if $50–200M of CAPEX and substantial transport costs are assumed (assumes $50–200M of CAPEX (based on higher-end estimates provided in conversations with industry, driven by need to build additional silo capacity and infrastructure). Assumes $8–10 per tonne of cement of incremental OPEX, based on $29–31/tonne of clay cost to transport 200 km, estimated by Scrivener, et al. (2019), assuming LC3 mix is 30% calcined clay by weight. With $50–200M of CAPEX instead of ~$15M for LC3, excluding incremental transportation cost, plants save ~$14–19 per tonne. With cost to transport materials 200 km, savings fall to ~$4–11. Calculations made using assumptions given in K. Scrivener, et al. (2019). Financial Attractiveness of LC3. https://lc3.ch/wp-content/uploads/2020/10/2019-LC3FinancialAttractiveness-WEB.pdf.)

year as of 2021–22, theoretically just enough to replace ~30% of cement volume by weight. [29] However, fly ash supply is expected to decline precipitously as the power sector transitions away from coal, meaning the future supply of these conventional SCMs will not be available in sufficient quantities. Indeed, these inputs are already among the more expensive SCMs. Supply shortfalls could drive further price increases and create cost and schedule risk for projects if cement cannot be supplied in time, deterring use.

Scale-up can rely on a combination of approaches: [30]

- **Alternative sourcing of traditional substitutes**. Shortages of fly ash can be addressed by expanding ponded coal ash use, which is allowed under current ASTM standards. Extraction of ponded ash could be part of brownfield remediation programs for legacy coal infrastructure, though efforts must navigate environmental and health risks and the associated potential for liability. [xcii, xciii]
- **Expanded use of emerging substitutes**. Calcined clays and natural pozzolans are widely available in many regions and can accordingly replace substitutes that are likely to be in shorter supply in the future while potentially offering even more favorable economics. [xciv]

Efficiency measures

Efficiency measures could also scale by the early 2030s—they offer the potential to reduce emissions by up to 5% at minimal cost to the industry. A representative mix of 24 efficiency levers, including process control, more efficient internal transport systems, and high-efficiency motors and fans, could abate ~2–5% of emissions by 2030 without increasing the cost of production and potentially driving modest savings per tonne of cement. [31]

Steeper efficiency improvements will be more challenging. Because of the long lifetimes of existing plants, more radical reconfigurations of plants to improve efficiency are unlikely to be economical in many cases. [xcv] Interventions can involve technical tradeoffs (e.g., increasing the number of preheating stages can improve heat recovery but also increase electricity consumption) or encounter economic barriers (e.g., technologies like waste-heat recovery are commercially available but have not been adopted at scale because of their cost). [xcvi]

Alternative fuels

Alternative fuels also have near-breakeven economics and could abate ~5–10% of emissions by 2030 with aggressive deployment, but community impacts must be considered. [32] Waste-based fuels like tires, waste oils, and plastics are already widely used, and ~25% of waste tires in the U.S. may already be used in cement production. [xcvii] These fuels can offer modest economic advantages when burned in the kiln because of their high heat content relative to other fuels. With marginal economics at baseline, high tipping fees for waste disposal can create a strong economic incentive for using waste fuels in cement kilns and have been a key driver of the more rapid uptake of alternative fuels in Europe. Jurisdictions with high waste disposal costs will also offer favorable conditions for more rapid deployment in the U.S. [xcviii, xcix]

Biomass fuels also have marginal cost implications per tonne of cement and can thus enable emissions

29 ~25 MT of fly ash was produced in 2021, and ~3 MT of granulated blast-furnace slag was available for sale in 2021. Collectively, 28 MT of conventional SCMs could represent ~30% of the mass of cement produced annually in the U.S., assuming 100% utilization in cement. Competition from other sectors, which could drive up the price of fly ash beyond what can be economically used in cement mixes, means the upper bound for utilization is likely to be considerably lower. Fly ash availability estimated from Adams, Thomas H (2022). "Coal Ash Recycling Rate Increases Slightly in 2021; Use of Harvested Ash Grows Significantly." American Coal Ash Association. https://acaa-usa.org/wp-content/uploads/2022/12/News-Release-Coal-Ash-Production-and-Use-2021.pdf. GGBFS production from U.S. Geological Survey (2021). Mineral Yearbook: Iron and Steel Slag. https://www.usgs.gov/centers/national-minerals-information-center/iron-and-steel-slag-statistics-and-information.

30 Scale-up of clinker substitutes could require expansion of quarries and mining facilities, with associated energy and environmental justice concerns. Potential EEJ implications are considered at a high level in Section 3.c, but this analysis was not scoped to assess these implications in detail.

31 These findings are consistent with other studies that suggest efficiency measures could abate ~5% of emissions by 2030 or 2040. See, e.g., Hasanbeigi, Ali, and Cecilia Springer (2019). Deep Decarbonization Roadmap for the Cement and Concrete Industries in California. Global Efficiency Intelligence. https://www.climateworks.org/wp-content/uploads/2019/09/Decarbonization-Roadmap-CA-Cement-Final.pdf.

32 Representative scenario finds potential for ~7% reduction in emissions by 2030, assuming alternative fuels share can expand to provide 35% of heat energy by 2030 on a trajectory to match the EU's 50% share by 2050. Detailed assumptions are provided in Appendix A.

reductions at minimal cost, though the availability of cheap biomass is limited and could be a constraint on deployment. [33] A recent study estimated that substituting biomass for 20% of coal content in kiln fuel mixes nationwide could reduce emissions by 4.3 MT CO2 per year (~6% of annual emissions), but noted that the total U.S. supply of fruit stones and nut shells, the optimal biomass feedstocks given their high heat content, could offset just 2.7 MT CO2 per year. [c]

Alternative fuels also come with air quality implications that need to be addressed. Combustion of tires, waste oils, and plastics has the potential to release additional air pollutants, potentially adversely affecting surrounding communities (discussed in Section 3.b). [ci, cii] This report does not estimate the cost of additional potential pollution-control equipment for fuel conversions, but these costs could be substantial. It should also be noted that a cement kiln that burns alternative fuels may be subject to different air emissions regulations, depending on the specific alternative fuels burned. As a result, the cost implications of thoughtful environmental stewardship may sometimes limit the uptake of alternative fuels.

Collectively, scaling clinker substitution, efficiency measures, and alternative fuels in line with an aggressive decarbonization pathway could require $25–60M of investment per plant—~$3–6B of total investment by the early 2030s. [34]

Liftoff for clinker substitution, efficiency measures, and alternative fuels

With clear demand from coordinated procurement, these currently deployable measures could rapidly achieve Liftoff. Large-scale buyers, particularly trusted government first movers like state DOTs, can lead with the initial adoption of lower-carbon blended cements, particularly ternary blends and blends using newer materials like calcined clays. Large buyers can incentivize uptake by ready-mix concrete suppliers and contractors by requiring low-carbon cement in project specifications and working with their lower-tier suppliers to facilitate adoption. An initial demand signal can be followed by rapid uptake in the rest of the market as customers follow the lead of first movers and cement plants convert production to lower-carbon blends, phasing out clinker-intensive products. (Key challenges and reasons why the market has not yet seen aggressive adoption are considered in Chapter 4.) If more aggressive blended cements follow the same trajectory as PLC, market share could double year-over-year once the critical tipping points are hit.

33 Analysis is based on economics for woody biomass (est. $41/ton). Detailed assumptions are in Appendix A. Other forms of biomass with higher heat content (e.g., stone fruits, nut shells) may be better suited to the fuel mix in cement kilns. Discussed in Pisciotta, Maxwell, et al. (2022, July). "Current state of industrial heating and opportunities for decarbonization." Progress in Energy and Combustion Science 91.

34 Assumes ~$10M of CAPEX required for a kiln bypass for alternative fuels and $15–50M of CAPEX for clinker substitution (based on estimated costs for mine or quarry expansion and additional storage and grinding equipment, both outside-in estimates and estimates provided in conversations with industry). There is significant potential for variability in CAPEX on a site-specific basis, depending on the local availability of materials and existing infrastructure. In outlier cases, $100–200M+ could be required. Sizing also assumes that cost per plant does not change with plant size, based on the assumption that similar equipment is required regardless of plant size. Detailed CAPEX assumptions are provided in Appendix A.

Track B: CCUS

Key takeaways

- **CCUS is a promising lever for cement decarbonization given the U.S. policy environment.** Industry believes CCUS will be critical for decarbonizing the ~60% of cement emissions intrinsic to the calcination process.
- **The economics are challenging today.** CCUS could come with ~$35–75 of incremental cost per tonne of CO2 and ~$25–55 per tonne of cement,[35] even with 45Q.
- **Liftoff will depend on coordinated procurement by large buyers to address challenging economics** by supporting necessary premiums and unlocking capital formation at the $0.5–1.0B per plant scale required.

The industry expects CCUS to play a key role in decarbonizing cement, but the technology is in the early stages of demonstration and deployment. Published industry and third-party roadmaps for the sector highlight CCUS, including retrofits of existing plants and incorporation into new builds, as a critical lever, potentially driving ~50–60% or more of cement decarbonization by 2050 (in the absence of alternative approaches).[ciii, civ, cv] But economics are challenging, and business models still need to be validated for plant operators and investors without experience with the technology. Liftoff is not assured in the absence of government financing, incentives, and demand for low-carbon materials.

Government financing, incentives, and demand will be critical in accelerating CCUS deployment in the cement industry. Public funding can help enable initial commercial-scale deployments in the U.S. The 45Q tax credit offers $85 per tonne of CO2 captured and permanently stored, improving the economic proposition of CCUS and helping to unlock the private sector business case for deployment. Large-scale procurement of low-carbon materials can create an enduring demand signal and potentially support cost premiums that may be needed for projects to be economically viable.

35 Based on analysis for CCS. Economic analysis was also performed for CCU and is discussed in the body of this section.

Figure 3.4: CCUS economics

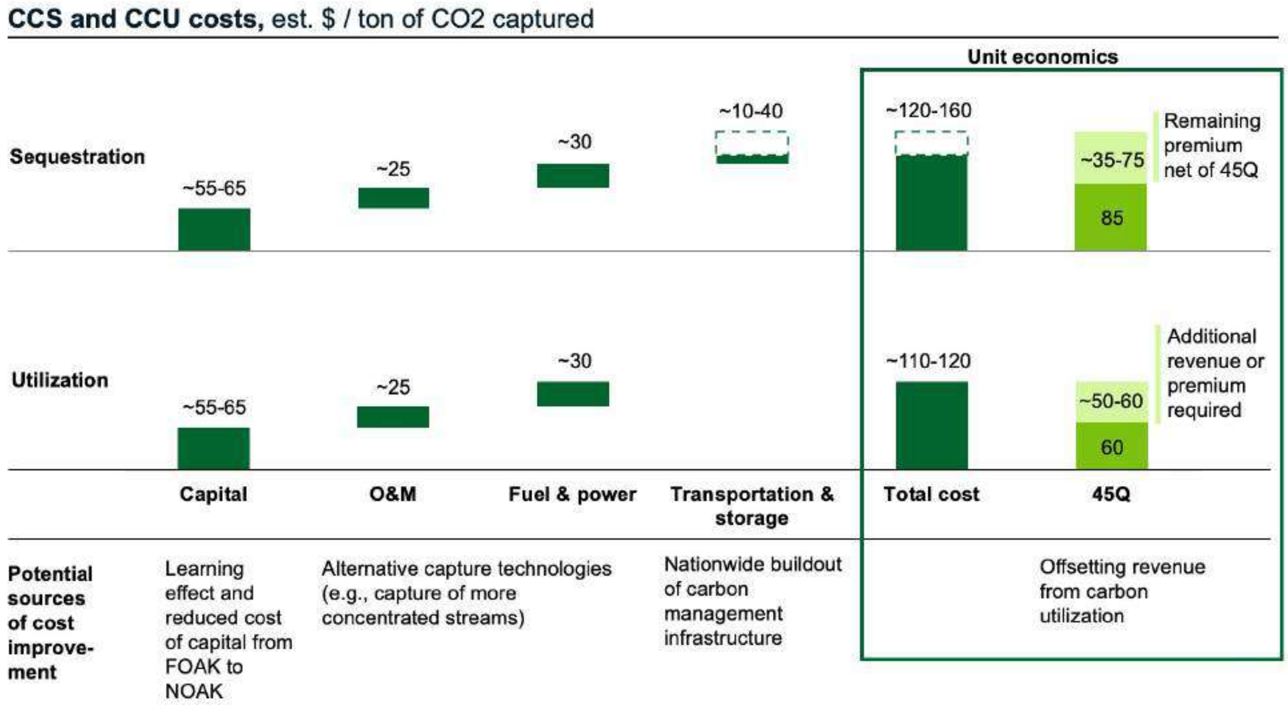


Figure 3.4. Illustrative economics for CCS and CCU deployments at a representative 1.5 MTPA cement plant. Figures for carbon capture are based on NETL 2023 modeling for 95% capture at a preheater/precalciner kiln fueled with coal and coke, using the CANSOLV amine-based post-combustion system. Capital costs are adjusted to reflect a 12-year payback period, consistent with what investors have said they will likely be willing to underwrite, using capital recovery factors provided by the Energy Futures Initiative. Transportation and storage cost of ~$10–40 per tonne of CO2 is assumed, consistent with the Carbon Management Liftoff report. Buildup yields a cost of ~$110–120/t CO2 without and ~$120–160 with transportation and storage. Assumes the project can capture the full value of the 45Q tax credit ($85/t CO2 for CCS and $60/t CO2 for CCU). In practice, the value of the tax credit that a CCU project can capture is contingent on a life cycle assessment of displaced emissions by NETL and FECM and could be a fraction of the full $60 potential credit. The figure for CCU is, therefore, a low-end estimate for the cost-revenue gap to bridge, as projects may require both additional transport infrastructure to transport captured carbon to another facility and likely will not be able to capture the full $60 value of the tax credit due to the volume mismatch between the CO2 captured and the CO2 that can be utilized with current technologies. Specific methodology is provided in the appendix. Sydney Hughes, and Patricia Cvetic. (2023, Mar.). Analysis of Carbon Capture Retrofits for Cement Plants. NETL. Energy Analysis | netl.doe.gov. Jeffrey D. Brown et al. (2023, Feb.). Turning CCS projects in heavy industry and power into blue-chip financial investments. Energy Futures Initiative. EFI – CCS Report (energyfuturesinitiative.org).

CCUS deployments necessarily drive incremental costs. Capturing and storing 95% of emissions at a representative 1.5 MTPA cement plant could cost ~$35–75 per tonne of CO2 and ~$25–55 per tonne of cement (equivalent to a ~20–40% premium on a $130 per tonne base price), even with the benefit of $85 per tonne of CO2 from the 45Q tax credit. CCS systems would thus need to achieve ~30–45% cost downs or corresponding revenue uplift for projects to break even with 45Q support. Without 45Q, capture and storage could cost ~$120–160 per tonne of CO2 and ~$85–120 per tonne of cement (~70–90% premium).[36, cvi, cvii]

High costs have three primary drivers:

- **Upfront capital costs**: A CCUS project can require $0.5–1B in CAPEX, and capital costs can account for ~50–55% of the total (excluding transportation and storage), driven by the cost of construction and the high cost to finance projects with a shorter payback period (e.g., 12 years required for projects to be economically viable with 45Q support). Total capital cost per tonne of CO2 is ~$55–65 with a 12-year payback period compared to ~$45–50 with a 30-year payback (~20–25% higher).[cviii]

36 See Figure 3.4 for a discussion of the methodology used for cost analysis. A detailed methodology is provided in Appendix B.

- **Operating costs from substantial fuel and power consumption**: Fuel and power needed for energy-intensive capture processes account for ~20–25% of levelized costs (excluding transportation and storage) and are particularly exposed to inflationary effects. [cix] In some cases, high energy demand could also drive additional costs not accounted for in the NETL modeling, such as the need to build a captive power plant if sufficient power cannot be drawn from the grid. [cx]

- **Potential for high CO2 transportation and storage costs**: Transportation and storage costs can vary widely based on site-specific conditions, such as whether the plant has access to an existing Class VI well for sequestration, how far away that well is, and how much additional pipeline and other supporting infrastructure needs to be built out. This analysis assumes $10–40 per tonne of CO2 in transportation and storage costs, consistent with prior NETL modeling and the Carbon Management Liftoff report, but the upper bound could be significantly higher for projects in less favorable geographies. [cxi, cxii]

However, industry is confident that CCUS systems can be deployed with minimal opportunity cost from plant downtime. Conversations with industry suggest CCUS systems can be built in parallel to operating plants and integrated during the planned ~2–3 weeks of annual downtime for relining of the kiln, which keeps opportunity cost from shutdowns to a minimum. [cxiii] If more substantial overhauls of the plant footprint are required, opportunity costs from lost operations could be significant, as discussed in Chapter 2.

Alternative CCUS technologies could eventually enable lower-cost deployments. Preliminary studies suggest that alternatives to traditional post-combustion amine-solvent systems like oxy-combustion and calcium-looping systems could be cheaper to build and operate, though these technologies remain at earlier stages of deployment readiness and public data on cost and performance remain limited. [37, cxiv]

Carbon utilization offers another potential route to improve project economics if high-value products can be produced. Using captured carbon to manufacture valuable products, CCU applications could generate additional revenue streams to help offset costs. Assuming it can capture the full $60 per tonne of CO2 45Q tax credit for carbon utilization projects, a CCU deployment would need to bridge a cost gap of ~$50–60 per tonne of CO2 and ~$35–45 per tonne of cement. However, this calculation is a low estimate: the value of the tax credit that CCU projects can capture is contingent on a life cycle assessment evaluated by NETL and FECM, and projects accordingly may not capture the full $60 value. CCU projects may also incur additional costs associated with the transportation of captured carbon to separate facilities and the operation of those facilities that will have to be offset by revenues.

The U.S. has a growing start-up ecosystem focused on using captured carbon to "cure" cement, concrete, and other construction products, though these are still typically pre-cast applications with a smaller accessible market and competition from low-cost alternatives. Many of these technologies remain nascent—largely pre-pilot or early pilot stage or are deployed at limited scale—but could also see additional demonstration and deployment in the mid-to-late-2020s, consistent with Liftoff in the 2030s.

CCUS Liftoff is contingent on the market finding ways to reduce, offset, and otherwise manage these high deployment costs, and government action can play a critical role.

- Initial demonstration projects could be completed in the mid-to-late-2020s, supported by grants and other forms of public funding in addition to 45Q. These demonstrations can validate the technology and business model for cement companies and investors and could drive initial cost reductions, unlocking follow-on deployments in the 2030s and 2040s.

- A next, larger wave of deployments will likely remain focused on sites in optimal geographies, where

37 Twenty studies of various technologies were reviewed in the DOE Industrial Decarbonization Roadmap (p. 148). Estimates come from 2006 to 2020 and are not adjusted to FY22 dollars or harmonized but broadly suggest that alternatives to post-combustion amine-solvent capture can be significantly cheaper, potentially closer to ~$40–60 per tonne of CO2.

projects can benefit from lower transportation and storage costs enabled by existing carbon pipelines, Class VI wells, and economies of scale from nearby CCUS project clusters. Among other regions, parts of PA, CA, the Gulf Coast, and the industrial Midwest could offer favorable conditions for large-scale deployment (Figure 3.5). [cxv] Coordinated procurement will be critical to support necessary premiums and unlock the investment case for capital-intensive projects.

- Deployment at remaining, less favorable sites will come last, benefitting from the cost reductions driven by learning effects, commercialization of new CCUS technologies, and buildout of shared carbon management infrastructure while relying on coordinated procurement to enable investment and economic viability.

Figure 3.5: U.S. cement plants and CCUS infrastructure

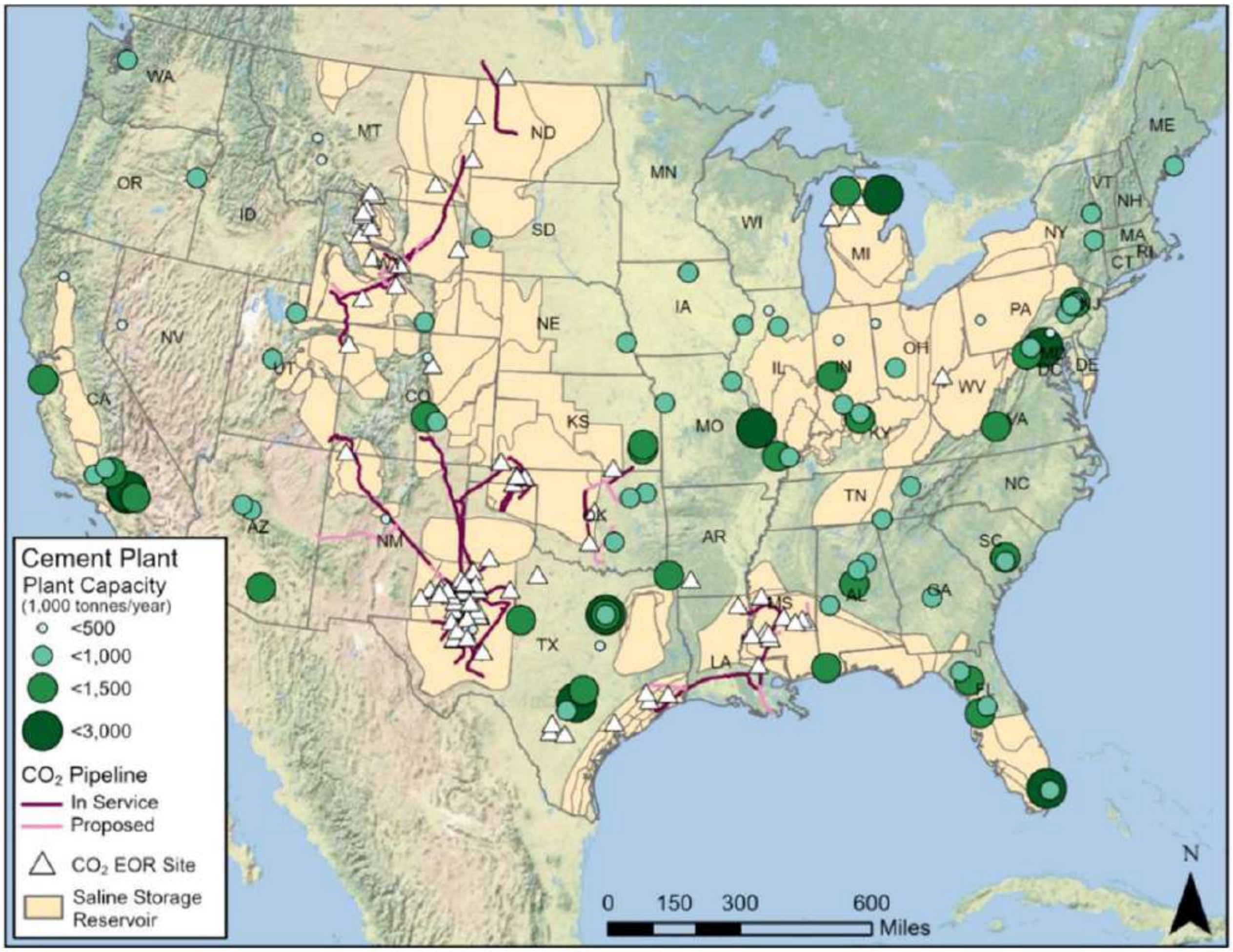


Figure 3.5. Map of U.S. cement plants overlaid with potential CCUS infrastructure, including saline storage reservoirs, current enhanced oil recovery (EOR) sites, and carbon pipelines. Note high-potential sites in CA, PA, the Gulf Coast, and the Midwest. Source: Sydney Hughes and Patricia Cvetic (2023, Mar.). Analysis of Carbon Capture Retrofits for Cement Plants. NETL. Energy Analysis | netl.doe.gov

Scaling CCUS across the entire industrial base could require ~$2–5B of investment by 2030 to support an initial 3–5 demonstrations, followed by up to an additional ~$55–100B of investment by 2050 for deployment at remaining and potential new-build plants (not accounting for potential reductions in capital costs or scale-up of alternative technologies in parallel).[38] Scale-up of CCUS could come with additional concerns from the public about environmental, health, and justice impacts, and projects will have to engage proactively with communities

38 Methodology for capital formation estimates provided in Appendix C.

and the public to ensure concerns are addressed (discussed in greater detail in Section 3.c and Chapter 4).

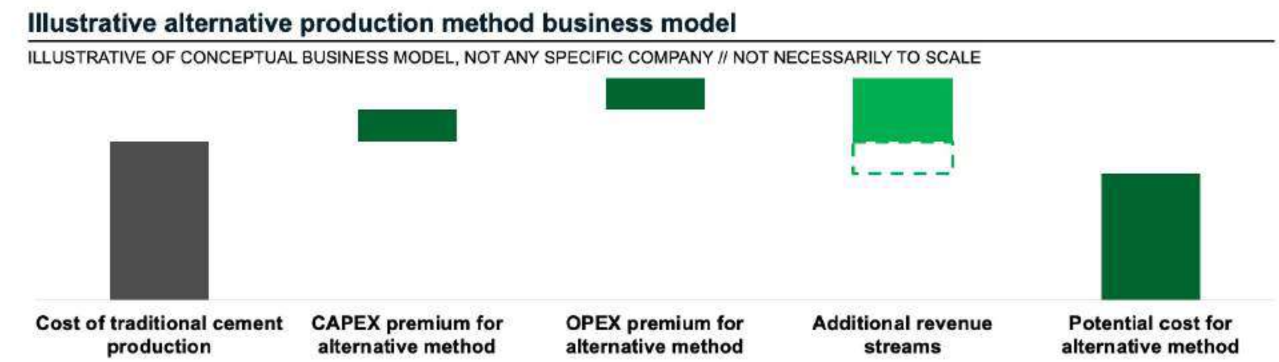
Track C: Alternative production methods for traditional cements

Key takeaways

- **Alternative production methods are still nascent, but could also scale in the 2030s.** To achieve Liftoff alongside CCUS, these technologies must demonstrate technological and economic viability commercially and prove they can enter the market under existing standards.
- **Greenfield plants will be capital-intensive—potentially ~$0.5–1.0B of CAPEX per deployment.** Coordinated procurement will again be critical to support premiums for FOAK deployments and enable capital formation.

Alternative production methods for traditional cement are emerging and could scale rapidly in the 2030s, provided they meet key milestones in the mid/late 2020s. These methods use fundamentally different approaches to produce drop-in replacements for traditional Portland or similar cements. They include alternative feedstocks, electrochemical production systems, and other alternatives to emissions-intensive rotary kilns (discussed in Chapter 2). [cxvi] Liftoff in the 2030s will require continued performance improvements, cost reductions, and significant public financial support.

Figure 3.6: Economics of alternative production methods



	Cost of traditional cement production	CAPEX premium for alternative method	OPEX premium for alternative method	Additional revenue streams	Potential cost for alternative method
Potential drivers of economics		CAPEX premium for FOAK plants (novel design) High cost of capital	More expensive parts of process (e.g., potentially from greater energy use)		If alternative methods can achieve sufficient cost-downs from FOAK to NOAK and/or generate sufficient offsetting revenue, **could achieve cost-parity or potentially improvement over traditional production**
Opportunities to improve economics		Learning effect and reduced cost of capital from FOAK to NOAK	Learning effect and supply chain maturation, enabling more efficient production	Selling byproducts of process (e.g., SCMs) to generate alternative revenue streams	

Figure 3.6. Illustrative economics and business model for alternative production methods. Alternative production methods could come with initial CAPEX and OPEX premiums compared to traditional production but can achieve parity by reducing these premiums and generating offsetting sources of revenue (e.g., production of SCMs and other valuable byproducts). Based on conversations with start-ups and investors pursuing alternative production methods. Figure does not reflect any one company or business model and is based on anonymized and aggregated information from multiple companies. Quantitative estimates are not provided due to limited performance history and public data.

Alternative production methods will have to meet key milestones with initial demonstrations in the mid/late-2020s to deploy on the timeline envisioned:

Performance: These technologies must demonstrate consistency with traditional cement products. They must work at commercial scale and yield products close enough to drop-in replacements for traditional Portland cements to enter the market under existing standards and with customers' trust. If this latter condition is not met, the timeline for broad market adoption could be pushed out significantly, as is the case with the alternative chemistries in Track D.

Competitive economics: Alternative production methods must achieve competitive economics with traditional production methods and CCUS. FOAK deployments will likely see a premium compared to traditional production, driven by a combination of high CAPEX (~$0.5–1B for a greenfield plant at commercial scale, potentially compounded by high financing costs) and an OPEX premium (e.g., from increased power consumption for energy-intensive processes). Business models generally assume some combination of the following:

- CAPEX premiums can be reduced from FOAK to NOAK by learning effects, improved financing conditions, and reduced cost of capital.
- OPEX premiums can be reduced by learning effects, economies of scale, and supply-chain maturation (in particular, the availability of process-optimized components that can improve plant efficiency).
- Remaining premium can be offset or more than offset by revenue from the sale of process byproducts (e.g., SCMs and other construction materials).

Coordinated low-carbon procurement will still be required to enable Liftoff by supporting the premium needed for initial deployments and providing a demand signal to attract capital at the multibillion-dollar scale required. These technologies could achieve Liftoff as follows:

- Initial commercial-scale demonstrations are launched in the mid-to-late-2020s, potentially with government funding and enabled by large-scale low-carbon procurement. ~3–5 technologies would demonstrate viability against key milestones, help achieve initial cost reductions, and prove competitiveness with traditional production methods and CCUS.
- If the economics prove viable and competitive, these technologies could scale with new-build plants in the 2030s and 2040s, either licensing the technology to incumbents or attempting to take market share themselves. The strong demand signal from coordinated government and private-sector procurement will again play a critical role in mobilizing required capital.

Liftoff could require ~$2–5B by the early 2030s for an initial ~3–5 demonstrations, with up to an additional ~$55–100B of investment by 2050 for new-build plants to decarbonize the full industrial base (trading off with CCUS deployments depending on whether site-specific conditions favor CCUS or an alternative production method).

Track D: Alternative chemistries

Key takeaways

- **Alternative binders to traditional clinker could have substantial abatement potential, but are far from widespread adoption.** Though they can build initial market share and scale in non-structural niches, these materials could face a ~10–20+ year adoption cycle to be accepted under widely used industry standards and achieve full-scale deployment in the broader market.
- **Accelerated customer adoption of performance-based standards like ASTM C1157 could significantly pull forward the adoption timeline.** Expanded use of performance-based standards in project specifications could allow novel materials to be deployed without developing new standards (potentially a 10+ year process).

Another set of technologies is similar to the alternative production methods following Track C, but, rather than produce drop-in replacements for cements currently in use, these technologies produce low-carbon cements with fundamentally different chemistries.

These alternative binder chemistries are generally nascent today, but could achieve Liftoff on a longer timeline after building initial momentum in niche applications and overcoming R&D, market adoption, and economic barriers.

Alternative chemistries are in different stages of technological maturity, market access, and economic viability, but all have significant progress to make before they can achieve large-scale deployment. Some materials, including magnesium oxides derived from magnesium silicates (MOMS) clinkers and certain bio-based and engineered clinkers, remain in the pre-pilot or pilot stage and will need additional R&D investment to progress. Others, including belite clinker, sulphoaluminate clinker, and alkali-activated binders, are commercially available, but only on a small scale. Performance is not yet well-characterized, and these materials are not approved for widespread use under existing industry standards, leaving them generally confined to a small subset of applications.

Alternative chemistries are on a longer track to Liftoff, and timelines will chiefly be determined by the industry standards process and adoption cycle:

- **In the short term, R&D investment—with government support—can facilitate the continuing development of alternative materials** that remain in the pilot or pre-pilot stage and conduct performance testing and validation of materials at higher levels of technological maturity.
- **When deployable, alternative chemistries can establish an initial market share in more accessible niches**, e.g., lower-risk, non-structural, pre-cast, and decorative applications (~15% of the market). This foothold can enable initial production scale and cost reductions, while allowing new materials to establish a track record of field performance.
- **In parallel, ASTM and AASHTO standards must be updated to allow alternative chemistries in a wider range of applications**, particularly building and transportation use cases accounting for >80% of demand. This process is expected to take 10+ years and will drive significant lead time for commercialization.
- **Even under optimistic assumptions about the timeline for approval, it could take until the 2040s for these materials to achieve a sizable market share**. Following approval under industry standards, customers can adopt alternative chemistries at a greater scale, potentially incentivized by demand for low-carbon construction and cases where alternative chemistries can offer economic or

performance improvements over traditional cement products. Rollout will likely be gradual, given the industry's slow adoption cycle, potentially taking another 10+ years.

Yet this timeline for full-scale adoption could be accelerated significantly by expanded use of performance-based standards, allowing alternative chemistries. Customers already have access to a performance-based standard, ASTM C1157, but it is not widely used. If customer education can convince a large share of the market to speed the adoption of ASTM C1157 and other performance-based standards, the timeline for broader adoption of alternative chemistries could be pulled forward significantly. Similarly, some large customers (e.g., large state DOTs like CalTrans) conduct their own testing and validation of materials independent of ASTM standards. Alternative chemistries that qualify under these supplemental testing regimes could grow their market share more rapidly.

Applied R&D opportunities on emerging technologies

There will be a continuing need for applied R&D across technologies and approaches. Some technologies like kiln electrification, expanded use of hydrogen, and some alternative SCMs and binder materials are at low TRL today and will require ongoing investment in basic R&D. Other critical technologies that are potentially closer to deployment, but still earlier stage, including CCUS, alternative production methods, and alternative binder chemistries, will require R&D investment both upfront and throughout the commercialization process to bring them to market and facilitate rapid deployment. Transformational technologies also have associated systems, facilities, and supply chains that will require their own R&D investment and improvement to ensure they can scale, integrate, and operate at maximal efficiency. Even technologies broadly or near-deployable today (e.g., clinker substitution, energy efficiency measures, alternative fuels) will require ongoing investment in applied R&D to improve performance and economics, maximize abatement potential, and speed commercialization by overcoming barriers encountered in the field.

DOE's Industrial Decarbonization Roadmap identifies key areas of focus for R&D investment across CCUS, low-carbon fuels and feedstocks, electrification, and efficiency levers, achieving impact on three time horizons:

- **"Near-term" (2020–25) needs**: support for low-capital measures (e.g., continued improvements in energy efficiency and waste-heat recovery), lower-carbon fuels and process heat (e.g., clean hydrogen, greater use of biofuels), and improvements to CCUS technology to enable more cost-effective capture on dilute emissions streams.
- **"Mid-term" (2025–30) needs**: development of increasingly ambitious low-carbon cement blends, routes for improved material-use efficiency and flexibility, process adaptations (e.g., precalciner electrification, alternative heating approaches, large-scale use of hydrogen), and advanced CCUS capabilities (e.g., oxy-combustion and indirect calcination, large-scale utilization).
- **"Longer-term" (2030–50) needs**: development of a circular approach for concrete, breakthrough heating approaches like kiln electrification and large-scale use of clean hydrogen, and innovative carbon capture and utilization approaches.

Although impacts will be felt on different timelines, early and sustained investment in all key areas will be critical to delivering technological improvements that can expedite deployment, improve economics and deployment-readiness of key levers, and unlock breakthrough approaches to accelerate decarbonization.

Section 3.b: U.S. leadership and technology export potential

With aggressive action, the U.S. can lead the world in cement decarbonization. Technologies developed, commercialized, and scaled domestically can be exported to address the ~7–8% of global carbon emissions from cement. Scaling low-carbon cement technologies worldwide will require business models that reflect other countries' economic and resource constraints, particularly in the developing world.

International cement decarbonization roadmaps lean heavily on technologies where the U.S. can play a key leadership role (examples reviewed in Figure 3.7). Published roadmaps suggest CCUS could abate ~35–50% of emissions, new processes ~5–15%, and material substitution ~5–15% (Figure 3.7).

Figure 3.7: International decarbonization pathways for cement

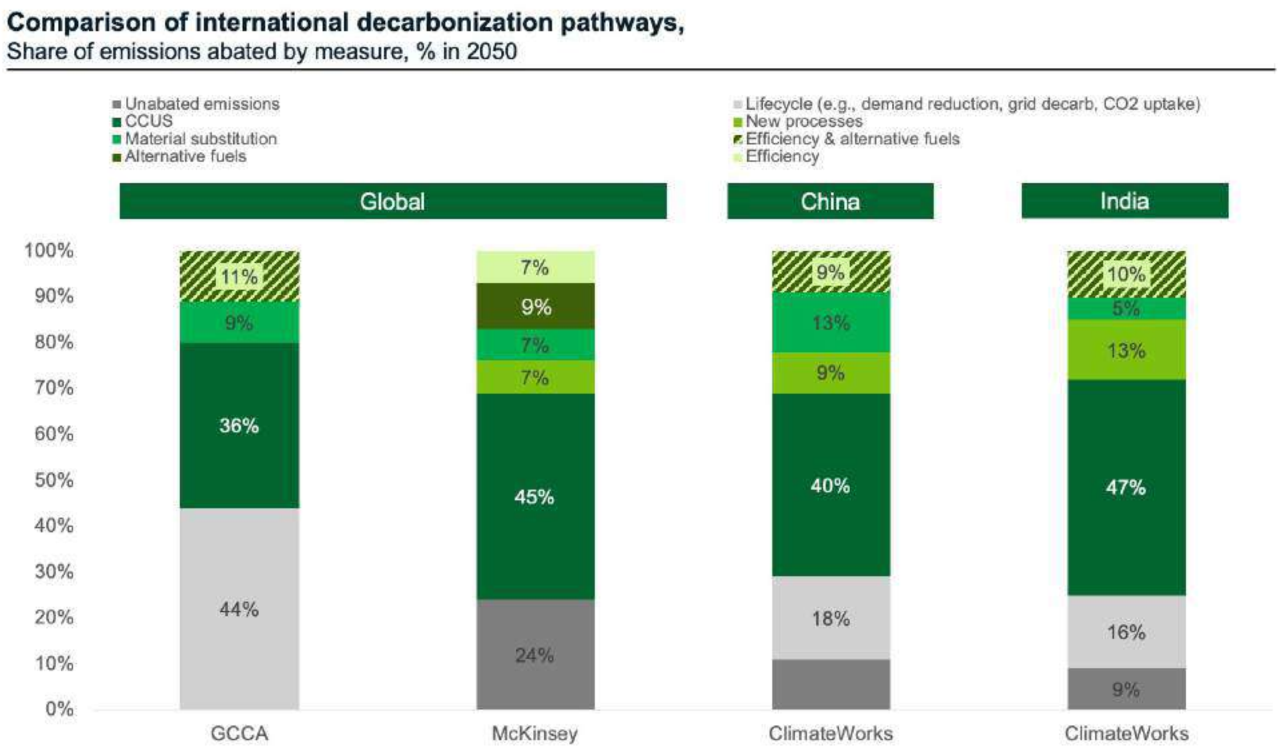


Figure 3.7. Comparison of modeled international and other-country decarbonization pathways for cement by 2050. CCUS is one of the largest drivers of emissions reductions in all cases, accounting for ~35–50% of abatement.
Sources: Global Cement and Concrete Association (2021). Concrete Futures: The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete. https://gccassociation.org/concretefuture/wp-content/uploads/2021/10/GCCA-Concrete-Future-Roadmap-Document-AW.pdf. Czigler, Thomas, et al. (2020). "Laying the foundation for zero-carbon cement." McKinsey and Company. https://www.mckinsey.com/~/media/McKinsey/Industries/Chemicals/Our%20Insights/Laying%20the%20foundation%20for%20zero%20carbon%20cement/Laying-the-foundation-for-zero-carbon-cement-v3.pdf. ClimateWorks Foundation (2021), "Decarbonizing concrete: Deep decarbonization pathways for the cement and concrete cycle in the United States, India, and China," https://www.climateworks.org/report/decarbonizing-concrete/.

In the short term, the U.S. can focus on commercializing and exporting the highest-impact measures that are currently deployable:

- **Clinker substitution**. The U.S. can help accelerate the global deployment of clinker substitutes by domestically validating and scaling more aggressive low-carbon blends and new SCMs like calcined clays, demonstrating technologies and business models for international use. Realizing the ~20–30% abatement potential of more aggressive clinker substitution worldwide could cut ~1.5–2.5% of all global CO_2 emissions, using technologically proven measures with a strong economic case today.[39]

39 Based on 20-30% of ~7–8% of global emissions.

Longer term, the U.S. could have a transformative impact in accelerating global cement decarbonization by pioneering two deep decarbonization business models for export:

- **Low-cost CCUS**: A U.S.-developed business model for CCUS that does not require a substantial premium or cost support could be transformative for global cement decarbonization. The U.S. is positioned to lead the world in CCUS deployment across industries, with the potential to achieve key technological and economic breakthroughs domestically before exporting internationally. With its favorable policy and market environment for carbon management, the U.S. could de-risk, scale, and reduce the cost of capture systems, including serving as the global proving ground for new, lower-cost technologies that can be deployed worldwide. Because many countries lack the extensive carbon storage capacity of the U.S., developing and commercializing cost-effective forms of carbon utilization at scale, in addition to capture, could be particularly critical for unlocking wider global deployment.
- **Alternative production methods**: If alternative production methods achieve Liftoff, including reaching cost-competitiveness with traditional cement production, they could also have significant export potential. American companies that successfully commercialize new low-carbon production methods could capitalize on market growth to build greenfield plants overseas.

Section 3.c: Workforce and energy and environmental justice (EEJ) implications

Decarbonization of the cement sector must occur in a way that ensures the creation of quality jobs and addresses the concerns and protects the health and environmental quality of fenceline communities, both to meet the country's climate, economic, and EEJ imperatives and to ensure the success of projects in these communities. This report takes a broad look at workforce and energy and environmental justice concerns to highlight the key opportunities that can arise from cement decarbonization, as well as the risks that must be mitigated to protect communities from additional harms.

This report does not include a comprehensive analysis of non-GHG emissions from cement production (e.g., other criteria air pollutants), specific industry workforce considerations, or technical solutions for EEJ concerns. This qualitative analysis is the beginning of what must be a robust discussion of how actually to implement a just decarbonization strategy. Additional work from many stakeholders is needed to outline tactical solutions toward a shared goal of a prosperous, just net-zero economy.

Companies, investors, and public- and private-sector stakeholders across the entire value chain are critical in determining whether projects advance a just and equitable transition to net zero or exacerbate existing injustices. "Pathways to Commercial Liftoff: Overview of Societal Considerations and Impacts" covers key workforce and energy and environmental justice (EEJ) considerations, recommends specific actions, and provides online resources. Detailed discussion of workforce and EEJ considerations in the context of industrial decarbonization is provided in the Pathway to Commercial Liftoff: Industrial Decarbonization report. The section below covers EEJ considerations and impacts specific to the cement sector.

The EEJ impacts of low-carbon cement projects depend on the benefits and harms incurred, who experiences them, and how the impacts alleviate or compound existing burdens. Industrial facilities are disproportionately concentrated in geographic areas with higher shares of households with low incomes and residents who are not white, which have historically borne the brunt of adverse health and environmental impacts without corresponding access to the economic benefits of industrial activity. [cxvii] It will be vital to anticipate and mitigate potential adverse effects of industrial transformation. Large-scale projects must be undertaken in consultation with local communities and with community buy-in to protect often marginalized populations and ensure project success.

Broadly, decarbonization and transformation of the industrial base for cement is an opportunity to address historical environmental injustices and contribute to frontline communities' health, environmental quality, and economic vitality. Specific dimensions are considered below.

Section 3.c.i: Economic impacts

Workforce and economic benefits

Decarbonization can be a positive opportunity overall for the cement and concrete workforce. Buildout of retrofits and greenfield plants can create good-paying construction jobs. As the broader construction sector faces pressure to decarbonize, decarbonizing cement production can position cement and concrete producers to continue to compete and thrive, helping to protect the ~210,000 jobs currently in cement and concrete products manufacturing. [cxviii]

Constraints in the construction workforce, particularly shortages of workers in skilled trades, could impede the scale-up of low-carbon technologies. [cxix, cxx] It will be critical for U.S. to invest in job training (especially Registered Apprenticeships), intentional efforts to recruit and retain underrepresented populations, and other measures to build the workforce pipeline for these essential trades, not just for cement but for decarbonization of the economy and infrastructure buildout more broadly. Growing and maintaining the skilled workforce needed to achieve climate and industrial strategy goals will be contingent upon creating good-paying jobs with opportunities for professional development and career advancement, as well as high safety standards. Success will require effective collaboration between industry, labor and worker-serving organizations, and government. [cxxi]

It will also be vital to ensure that jobs and other economic benefits of sector transformation flow to frontline communities. Project developers can engage in community benefits agreements and develop community benefits plans to make commitments about the kinds of local benefits they will provide, as well as conditions of employment (including committing to wages, benefits, and health and safety standards) and job-training investments. [cxxii] Job training, such as registered apprenticeship programs, intentionally inclusive recruitment and retention strategies, such as financial and non-financial supportive services, and negotiated agreements between community stakeholders, are all critical tools to enable historically disadvantaged and underrepresented communities to participate in the economic benefits of local development. [cxxiii]

Cost of goods

Because cement is a critical upstream input for a wide array of critical goods (e.g., infrastructure, housing), impacts on cost can have far-reaching implications. Some interventions (e.g., clinker substitution and alternative production methods, provided they can achieve economic competitiveness compared to traditional production methods) could reduce the cost of cement production, with the potential for savings to eventually pass downstream to consumers. Though downstream cost implications may be limited (as cement typically accounts for a small share of overall project costs), in cases where structural cost increases may be incurred (e.g., CCUS), efforts must be made to protect consumers from cost increases, particularly those who are most economically vulnerable. In many cases, the 45Q credit, other tax incentives, and Infrastructure Investment and Jobs Act (IIJA)[40], also referred to as the Bipartisan Infrastructure Law (BIL) / IRA programs will help to defray costs and insulate consumers from cost increases.

Section 3.c.ii: Health and environmental quality impacts

Air quality

Cement production has historically been associated with significant air-quality concerns and harm to surrounding communities, including emission of SO_2, NO_x, and CO. [cxxiv] Decarbonization efforts can come with additional risks to be mitigated and opportunities to address air-quality concerns associated with cement production. Alternative fuels, particularly waste-based fuels like tires, plastics, and waste oils, can come with air pollution risks that must be mitigated. [cxxv, cxxvi, cxxvii] Carbon-capture retrofits and shifts away from kiln-based production methods also offer opportunities to improve local air quality by implementing new pollution-control and abatement measures (e.g., "scrubbing" of NO_X, SO_2, and particulate matter before carbon capture). [cxxviii, cxxix]

40 Infrastructure Investment and Jobs Act, Pub. L. 117-58, 135 Stat. 429 (2021)

Raw materials

Building out the supply chain for input materials also presents both risks and opportunities for the health and environmental quality of frontline communities. SCMs are disproportionately sourced in vulnerable communities, creating added risk and a particularly strong equity imperative to anticipate and address potential harms. Some SCMs and new feedstocks could require the development of new mining and quarry operations and supporting infrastructure, and any such redevelopment must be done in a manner that does not compromise the health and environmental quality of surrounding communities. [cxxx]

Using ponded coal ash as an SCM can contribute to the remediation of brownfield sites, improving the economics of costly remediation projects and providing a safer way of disposing of hazardous materials. [cxxxi] Efforts must be undertaken to ensure that ponded ash is handled safely and that redevelopment projects are undertaken consistent with the health and safety of surrounding communities.

Section 3.c.iii: Carbon management concerns

CCUS will likely be a major part of the decarbonization pathway for the cement sector. The public may have broader concerns about carbon management projects, including potential health and safety impacts of CO2 transport and storage infrastructure, the cumulative burden on local communities (e.g., extending the lifetime of emissions-intensive facilities), and potential financial support for companies with a poor track record on climate and environment. Successful delivery of CCUS projects will hinge on effective engagement with both local communities and the broader public to ensure risks and concerns are addressed. These potential risks, concerns, and approaches to public engagement and accountability are considered in detail in the Carbon Management Liftoff report. [cxxxii]

Chapter 4: Challenges and solutions

Key takeaways

- **Large-scale buyers, particularly government agencies, can develop shared standards for low-carbon materials** to enable informed and effective procurement.
- **Overall adoption cycle for new materials will have to be compressed from ~10–20 years to ~5–10** to meet aggressive deployment targets for the early 2030s**.** Accelerated adoption will require a combination of demand-side incentivization, market education, and technical assistance.
- **Capital-intensive deployments will require new procurement models with long-term offtake commitments to unlock required investment.** For example, a 10 to 12-year, ~$0.5–2.b offtake agreement could be at the scale needed to unlock investment to retrofit one representative 1–1.5 MTPA plant with CCUS or to support the construction of a greenfield plant using an alternative production technology.
- **Longer term, deep decarbonization technologies like CCUS could require initial government-backed interventions** to offset structural cost increases, including support from 45Q, premiums supported by low-carbon procurement, and updates to construction codes requiring low-carbon materials.

With concerted effort, the U.S. is positioned to recapture global leadership on low-carbon cement and lead on the commercialization of multiple key technologies. Stable policy support and favorable market and geological conditions make the U.S. the world's most attractive destination for CCUS today. In parallel, a vibrant U.S.-based startup ecosystem could bring revolutionary low-carbon cement technologies to market in the coming decades.

Rapid Liftoff of these technologies is possible, but contingent on overcoming six key challenges to compress adoption timelines for deployment-ready technologies and accelerate the commercialization of new approaches. Several additional challenges specific to CCUS are discussed in detail in the Carbon Management Liftoff report. These challenges include economic and commercial factors (e.g., cost uncertainty, demand uncertainty, lack of commercial standardization) and execution factors, (e.g., permitting lead times, limited transport and storage infrastructure, public concerns and opposition to projects).

Government action has a critical role in enabling solutions, leveraging both the power of government procurement and the government's ability to convene and coordinate key stakeholders across the value chain. Private-sector leadership will also be required to set ambitious goals and collaborate in overcoming barriers.

Figure 4: Challenges to Liftoff and potential solutions

Challenges	Potential solutions
1 **Lack of robust system to define low-carbon materials** makes it hard for large buyers to make informed procurement decisions	• **Establish shared standards and data infrastructure** to define and validate low-carbon cement and concrete products
2 **~10-20-year adoption cycle for new blends and materials** delays demand and corresponding investment in decarbonization	• **Invest in accelerated testing, validation, and demonstration** of low-carbon cements and concretes • Engage key end customers to **encourage requirement of low-carbon materials in project specifications**, including through adoption of performance-based standards • **Provide technical and financial assistance** to facilitate adoption in the broader value chain
3 **Informal, short-term procurement model** is not well-structured to attract long-term investment	• **Develop alternative procurement models** that provide direct offtake for projects
4 **Structural cost increases for CCUS and other approaches** may permanently increase cost to end users	• **Provide durable policy support** to address challenging economics • **Provide coordinated procurement** to support a long-term premium • **Update construction regulations** to require use of low-carbon materials in projects
5 **Technology, performance, and cost uncertainty** discourage deployment and investment	• **Provide support for early project development** and creation of archetypal business models and terms • **Provide continuing investment in R&D** for critical technology areas
6 **Lack of public support for projects,** driven by concerns about environmental and human health risks, EEJ and labor implications	• **Implement robust community benefits plans and agreements** that are responsive to public concerns, mitigate potential harms, and ensure accountability

Figure 4. Six key challenges and potential solutions highlighted in conversations with industry and key stakeholders across the value chain.

Challenge 1: The market lacks a robust system to define low-carbon materials, making it difficult for large buyers to make informed forward procurement decisions.

There is growing interest in the procurement of low-carbon cement and concrete products among government and private buyers, but markets broadly lack common, widely-scaled mechanisms for establishing and verifying which cement and concrete products qualify as sufficiently low embodied carbon. Without common standards and validation mechanisms, large buyers struggle to make informed procurement decisions and coordinate effectively to create a demand signal for industry.

Low-carbon procurement efforts rely on third-party "environmental product declarations" (EPDs), estimates of the embodied carbon of products (i.e., the emissions associated with their production, distribution, and use). [cxxxiii] Yet current EPDs come with key limitations, including:

- **Lack of standardization**. There is no single standard methodology to assess the embodied carbon of products in EPDs, making it challenging to compare cements and concretes during a competitive procurement process. The industry has expressed concerns that some EPDs are not effectively integrated with broader life cycle assessments, making it difficult to account accurately for the full life cycle impact of materials (e.g., the impact of durability and salvage or reuse potential). Challenges with standardization are compounded by fragmentation in the market, particularly in intermediate tiers of the value chain.
- **Limited data availability.** Data on emissions associated with specific inputs and production at specific facilities remains limited, making it difficult to produce accurate estimates of embodied carbon. Data may be available in many cases, but suppliers may not independently be incentivized or

resourced to make necessary investments in acquiring it. Without more robust data, some EPDs have historically relied on industry averages and have been unable to verify the true emissions content of products (though more recent efforts, e.g., GSA procurement standards, increasingly require facility-level data).

- **Limited accessibility for new products and facilities**. EPDs typically require a plant to have at least one year of operating history to provide needed data, which makes it challenging for technologies in the pilot stage or early deployment to receive EPDs and thus qualify for low-carbon procurement initiatives.

Solution 1: Establish shared standards and data infrastructure to define and validate low-carbon cement and concrete products for future procurement.

A shared standards regime to support low-carbon procurement will include three main elements outlined below, and federal efforts currently underway can provide a strong foundation for a long-term standards model.

- **Common definition of low-carbon cements.** Large government and industry buyers can convene to develop shared standards for what qualifies as low-carbon cement and concrete. Efforts can follow the lead of multiple actors, public and private, that have begun developing initial standards, including NIST, the First Movers Coalition (FMC) and GSA. FMC has already established a standard for low-carbon concretes used by its members in the construction and real estate industries, and GSA has set specific standards for "substantially lower embodied carbon materials" based on EPA's Interim Determination. [cxxxiv, cxxxv] It is important for standards to grow more stringent over time and set a sufficiently high bar to incentivize investment in deep decarbonization. A government-led or industry program after the model of EnergyStar could also provide voluntary certification of low-carbon materials that meet shared standards. [cxxxvi] With IRA funding, EPA is developing a carbon-labeling program for "substantially lower embodied carbon" construction materials. [cxxxvii]

- **Standardized approach and template for EPDs.** To implement these standards uniformly, the market must align on a common methodology for developing and validating EPDs. To capture the emissions impact of materials accurately, standard templates and methodologies should account for the impact of their full life cycle—including use in the field, potential reabsorption of CO2, and end of life, in addition to production—and incorporate digitized tracking for verification. A preliminary or provisional EPD mechanism will also be necessary to allow technologies at the pilot or early demonstration stage to qualify for low-carbon procurement.[cxxxviii] With IRA funding, EPA has led the initial work to establish standard practices for EPDs and can continue leading the market and shaping practices. [cxxxix] The Federal-State Buy Clean Partnership has convened 13 states and the federal government to harmonize procurement standards. [cxl, cxli]

- **Data collection and publication**. Development and widespread use of standardized EPDs will also require extensive collection and dissemination of data on emissions for various products. Large-scale government buyers can promote transparency by requiring the disclosure of emissions data as part of the procurement process. Efforts can build on existing EPD libraries like the Embodied Carbon in Construction Calculator (EC3) developed by Building Transparency and the federal LCA Commons to develop an industry-wide central, universally accepted repository. [cxlii, cxliii, cxliv]

Challenge 2: Historically, the industry has had a ~10 to 20-year adoption cycle for new blends and materials, which delays demand and subsequent investment in low-carbon production.

A multidecade adoption cycle will prevent the rapid deployment of clinker substitutes and delay the rollout of more novel materials. To realize maximal abatement potential and economic value by 2030, the adoption cycle for new blends and materials must be compressed from ~10–20 years to ~5–10 years.

The extended adoption cycle has three components:

- **Long lead times to update industry standards.** Updating ASTM and AASHTO standards is a lengthy process (historically 10+ years), imposing significant lead time for new materials to enter the market under prescriptive standards. [41] Standards are developed through a consensus-based process by committees composed of volunteer industry experts. Industry organizations are justifiably risk-averse about allowing the use of new materials, particularly where there are life-safety implications. Changing standards to accommodate new materials requires extensive testing, validation, and consensus-building with a range of stakeholders, which significantly pushes out the timeline for adoption.
- **Slow uptake by risk-averse end customers**. Even when new blends and materials are accepted under industry standards, end customers are risk-averse and typically slow to adopt new materials into project specifications because of potential risks to safety, performance, cost, and schedules. Large government buyers, particularly state DOTs, can play a critical role in bringing along customers and shifting the market, but they tend to be risk-averse given their need for materials to perform to high standards in the field and be durable under challenging environmental conditions. Private construction, engineering, and development companies are likewise often slow to adopt new materials that may come with performance and cost risk and have broadly been reluctant to adopt new standards (e.g., performance-based standards that could allow alternative chemistries) into their specifications.
- **Slow uptake by intermediaries (e.g., ready-mix concrete companies and contractors) for technical and risk reasons.** Ready-mix concrete companies and other contractors are often small businesses with little margin for error on projects, limited internal resources for testing and validation, and limited capacity and appetite to adapt to the technical requirements of new materials. Anecdotal evidence suggests this was a challenge even with the more modest changes to cement mixes under the PLC rollout: PLC blends were not always perfect drop-ins for existing practices, and using them successfully involved a learning curve, complicating deployment.

Solution 2: Pursue targeted interventions to compress the adoption timeline.

Three priority approaches could help increase confidence in new blends and materials, encourage end customers to accelerate adoption into specifications, including through the use of performance-based standards, and facilitate uptake by intermediaries:

Solution 2.a: Invest in accelerated testing, validation, and demonstration of low-carbon cements and concretes.

Government and industry can partner to expand and expedite testing, validation, and demonstration of more low-carbon cement blends and novel materials to speed acceptance under industry standards, build market confidence, and drive adoption. Accelerating this process will require a buildout of testing infrastructure, funding for additional large-scale material demonstrations, and more proactive engagement with industry standards organizations.

Minnesota DOT's "MnROAD" pavement test facility is a prime model for expanded testing. The facility includes segments of actively used roads and highways paved with different concrete and asphalt equipped with sensors to collect detailed data. These data can be used to evaluate material performance under a range of realistic deployment conditions. [cxlv] MnROAD is in the second year of a three-year effort to test concrete pavings made with several kinds of low-carbon cements, including PLC mixes with higher limestone content and blended cements with alternative SCMs (including some manufactured with sequestered CO2). Results will be published and used to inform and justify the adoption of new materials by state DOTs. [cxlvi]

41 See, for example, the extended timeline required to change and approve standards for Portland Limestone Cements.

Similar efforts on a larger scale will be needed to test additional blends in additional geographies. Testing and validating more materials would need to be done in parallel to enable rapid deployment. This could be unlocked via modest investments to build out parallel facilities and accelerate needed materials testing—for example, MnROAD's current operations are supported by ~$10M in grants. [cxlvii]

Government and industry organizations can engage more proactively with ASTM and AASHTO to ensure test results are rapidly incorporated into industry standards. NIST, DOT, or another relevant agency can lead outreach to socialize test results, identify gaps in testing, and prioritize future research accordingly. NIST's Low Carbon Cements and Concretes Consortium is already engaged in convening stakeholders for this kind of outreach.[cxlviii] Modest funding support for standards-setting organizations could also allow committees to meet more regularly and provide them with the resources to accelerate the review of new materials.

Once materials are validated, public funding can support demonstration projects for low-carbon cements and concretes in various use cases and conditions, with sites chosen for high public visibility and results widely publicized to build broader market confidence. Initial demonstrations could focus on horizontal applications like roads, highways, and pavers, then expand to lower-risk vertical construction like single-story buildings.

Solution 2.b: Engage key end customers to encourage the requirement of low-carbon materials in project specifications, including by adopting performance-based standards.

Concerted engagement with key customers and broader market education to encourage the inclusion of low-carbon cements in project specifications can shorten the adoption cycle. Industry organizations and key government agencies can lead outreach by forming a central clearinghouse for collecting and publishing technical and economic data, convening customers, and conducting active outreach to share information about new materials and build confidence. Efforts can focus first on the largest and most influential buyers of cement, particularly state DOTs, to have a maximal impact on the market. U.S. DOT and the Federal Highway Administration (FHWA) can lead in coordinating outreach to state DOTs and facilitating knowledge-sharing to raise ambitions, build comfort with new materials, and accelerate rollout.

Similar efforts could speed the uptake of performance-based standards to facilitate expanded market access for novel chemistries. Similar efforts could speed the uptake of performance-based standards like C1157 to facilitate expanded market access for novel chemistries. Again, U.S. DOT and FHWA can collaborate with NIST, other relevant agencies, and industry organizations to engage with state DOTs and encourage broader use of performance-based standards. A coordinated effort can facilitate information-sharing, quickly surface challenges, and quickly bring the full breadth of government and industry resources to bear to address them.

Solution 2.c: Provide technical and financial assistance to facilitate adoption in the broader value chain.

As the sector pursues more novel blends and materials, coordinated technical and financial support can help address the difficulties intermediate players in the value chain (e.g., small ready-mix companies and subcontractors) have with the rollout.

Industry organizations and governments can partner with small ready-mix companies and subcontractors to address the technical challenges of working with unfamiliar materials with distinct requirements. Local ready-mix, aggregate, and construction trade associations will be vital partners in any such effort. They can convene key players and serve as the central venues for training and outreach, proactively identify and address challenges, and collect and disseminate technical best practices.

Challenge 3: The procurement model for cement is not structured to attract the investment required for decarbonization.

Cement is traditionally purchased through "handshake" spot transactions, as the nature of the construction market disincentivizes long-term purchasing commitments (discussed in Chapter 2). According to investors, these kinds of short-term agreements are difficult to use as the basis for securing low-cost infrastructure financing.

Purchasing agreements are also adjudicated between intermediate steps along the value chain, where there is significant fragmentation. An end customer seeking to purchase cement for a project rarely, if ever, contracts directly with a cement producer, but instead with a construction firm that purchases cement through multiple layers of intermediaries, such as ready-mix companies and other subcontractors. As a result, it is difficult to establish bankable offtake commitments that directly link end customer willingness to pay for low-carbon cement to cement producers who need to invest to meet that demand.

Absent bankable offtake, the cement industry will struggle to attract investment at the scale needed for deep decarbonization projects. Therefore, establishing low-carbon procurement standards by large buyers is unlikely to be sufficient on its own. Coordinated procurement programs can address these challenges with an alternative purchasing model.

Solution 3: Develop alternative procurement models that provide direct offtake for projects.

To make the demand signal for low-carbon cement bankable for risk-averse investors and enable project finance at scale, large-end customers must develop a procurement model that provides greater offtake certainty for low-carbon cement plants. To de-risk projects sufficiently, such a model could need to have three main elements:

- **A direct, legally enforceable contract** between the cement plant and a creditworthy end customer (e.g., a government agency, large private customer, or large construction company);
- **Guaranteed offtake for most or all of a plant's output** for the investment period, with some guarantee regarding price; and
- **Active management of intermediaries in the supply chain** to ensure low-carbon cement products are used in the construction process, which could require off-takers to invest in improving visibility upstream in their project supply chains.

A range of options for such a model are available and actively explored by government and private-sector customers. Potential approaches include advance market commitments, direct procurement or structured offtake agreements, contracts for differences, contractual price guarantees, and advance purchase agreements for avoided carbon emissions.

Providing this guaranteed offtake with government procurement could require adopting alternative contracting models. Procurement experts at several federal and state agencies expressed concern that long-term offtake commitments could be at odds with acquisition requirements, but alternative contracting structures currently in use (e.g., Multiple Award Task Order Contracts and Indefinite Duration, Indefinite Quantity contracts already used by agencies to manage complex, long-term acquisition programs), could offer an alternative model. More complicated procurement mechanisms could require additional investment in the contracting shops at state DOTs and key federal agencies with less experience with these vehicles. [cxlix] Private buyers could have more flexibility in implementing new approaches but require greater coordination to build buyers' coalitions and collectively implement new procurement models (e.g., through forums like the First Movers Coalition). [cl]

A 10–12-year commitment worth $0.5–2.0B total could provide sufficient offtake assurance to enable a project finance model for a commercial-scale retrofit or greenfield plant using novel decarbonization approaches. For a CCUS retrofit of a representative 1.5 MTPA cement plant, a $0.5–1.0B total commitment over 12 years could cover the total cost of the premium beyond 45Q. [42] Over ten years, a ~$1.3–2.0B commitment could provide 100% offtake coverage for NOAK greenfield plants using alternative production methods or novel chemistries. [43] Guaranteeing offtake from FOAK plants could require a larger commitment to cover the cost premium of early deployments.

Challenge 4: Deep decarbonization technologies, particularly carbon capture, may involve permanent structural cost increases.

If cost declines do not bring costs of key technologies below expected revenues, projects will struggle to achieve long-term economic viability. As discussed in Chapter 3, CCS deployments could involve a structural cost increase of $35–75 per tonne of CO2 with 45Q (equivalent to ~20–40% premium per tonne of cement) and $120–160 per tonne of CO2 without 45Q (equivalent to ~70–90% premium per tonne of cement). Adding incremental and permanent cost increases to cement can create ongoing challenges to the economic viability of business models and deter investment in scale-up depending on the policy environment.

Solution 4: Establish policy and market models that offset structural cost increases.

Additional revenue streams or incentives may be required to enable the long-term economic viability of deep decarbonization technologies that come with these structural cost increases. Government and industry can work in tandem to pursue policy, regulatory, and market mechanisms that help address the structural costs associated with CCUS and other decarbonization measures. Three priority actions are detailed below.

Solution 4a: Provide durable policy support to address challenging economics.

Policy support can help bridge remaining cost gaps after long-term cost declines. Approaches could include an extension of 45Q or other market-based mechanisms. Policy support can stack with other measures, such as revenues from other products and premiums (discussed in Solution 4b), which may be particularly important if cost declines are more limited.

Solution 4b: Provide coordinated procurement to support a long-term premium.

Government procurement programs can set aggressive standards for low-carbon materials and provide additional funding to support premiums. At the federal level, the Biden-Harris Administration's Buy Clean Initiative seeks to leverage the government's purchasing power to spur expanded manufacturing of low-carbon materials, pursuant to the Administration's goal of achieving net zero in federal procurement by 2050. [cli] The Inflation Reduction Act provides $4.5B to support the procurement of low-carbon materials by GSA and U.S. DOT. [clii] At the state level, New Jersey's Low Embodied Carbon Concrete Leadership Act (LECCLA) provides a tax credit to concrete suppliers on government projects that provide quantifiable reductions in embodied carbon, while other states are phasing in similar programs. [cliii] Large private-sector buyers could adopt a parallel approach consistent with their decarbonization mandates.

However, passing a premium through multiple layers of intermediaries in the value chain will come with additional challenges. Intermediaries could impose additional premiums in each tier, diluting the effect of coordinated procurement. Success will likely hinge on the capacity of end customers to manage their supply chains more actively, which may require capacity-building in their procurement and contracting organizations.

42 Calculations are provided in Appendix B. Analysis assumes an offtake agreement would cover the remaining premium per tonne of cement after 45Q on cement sold by an existing plant.

43 Assumes alternative production methods can achieve parity with the current cement price of ~$130 per tonne, with a 10-year offtake to cover 100% of output for a 1–1.5 MTPA plant.

Solution 4c: Update construction regulations to require using low-carbon materials in projects.

State and local building codes and other construction regulations offer an opportunity to overcome cost barriers to decarbonized materials by prescribing their use in projects. [cliv] Building and construction codes already require certain materials, typically for safety reasons, and could set similar requirements for low-carbon cements and concretes.

Some jurisdictions have already begun to implement such a model. Portland, OR, requires Portland cement concretes used in city-owned construction projects to have embodied carbon below a maximum value for a given strength class, verified by a third-party EPD. [clv] Marin County, CA, adopted a building code that requires all concrete placed in the county to meet either a limit on cement or embodied carbon that scales with the specified compressive strength of the material. [clvi]

Because building and construction codes are generally defined at the state or local level, the change would likely be a slower process, working locality-by-locality. Efforts could start in large jurisdictions with the most construction activity to build market share and momentum, then try to achieve wider adoption nationwide. Under BIL and IRA, DOE has ~$1.2.b in funding to accelerate the adoption at the state and local level of traditional and innovative building energy codes, including zero energy codes and building performance standards.[clvii, clviii]

Challenge 5: Critical emerging technologies face performance and cost uncertainty. Others remain at low TRL.

Measures like CCUS, alternative production methods, and alternative materials as applied to low-carbon cement remain untested at commercial project scale in the U.S.; cement companies and investors will need to see technologies and business models de-risked before they pursue the substantial capital investments required for deployment. Cement companies are also unfamiliar with these technologies and will need to build comfort operating CCUS systems or new kinds of plants before they can deploy at scale. Other critical technologies are at low TRLs or will need further progress on applied R&D to achieve necessary cost and performance improvements for widespread deployment.

Solution 5a: Support early project development and create archetypal business models and terms.

Support for early deployments in CCUS, alternative production methods, and alternative chemistries will be needed to reduce technology and execution risks. Three to five commercial-scale projects could be needed for each technology to prove it can be operationally and commercially viable at scale. Billions of dollars are potentially available through BIL and IRA to support these initial deployments, helping offset high costs and improve the economic viability of FOAK projects. To ensure initial deployments have their maximal effect in de-risking business models for investors and unlocking follow-on deployments, it will be important to collect and publish technical and economic data from initial demonstrations to inform future investment decisions.

Similarly, developing standardized project and financing structures for these technologies can accelerate long-term buildout. Publication of project execution best practices, lessons learned, and project terms—particularly from projects that receive government support—can provide a replicable template for future deployments. [44]

Solution 5b: Provide ongoing R&D investment to advance transformative lower-TRL technologies and accelerate adoption across technologies.

Where critical breakthrough technologies remain at lower TRL, continuing R&D investment can accelerate progress towards technological maturity and ultimate commercial-scale adoption. Start-ups, academic research organizations, and relevant parts of the DOE and other federal agencies, including IEDO and

44 Also discussed in the Carbon Management Liftoff report in the context of carbon management projects.

ARPA-E, can help catalyze and drive breakthrough R&D efforts. Non-profit organizations can also play a role by continuing to highlight the importance of research into cement decarbonization, particularly the next wave of deep decarbonization technologies, and fostering collaborative partnerships between research institutions, industry, and government agencies. More detailed discussion of potential R&D priorities is provided in Chapter 3 of this report and in DOE's Industrial Decarbonization Roadmap. Additional discussion of challenges and solutions related to R&D is provided in the Pathway to Commercial Liftoff: Industrial Decarbonization report.

Challenge 6: Lack of public support for projects, driven by concerns about environmental and human health risks and EEJ and labor implications.

Fenceline communities and the public are often wary of industrial projects because of the history of adverse environmental, health, EEJ, and labor impacts they may bring. Ensuring community buy-in and addressing public concerns is not just an ethical imperative for developers–failure to build trust with the public can stymie project development, increasing costs by delaying progress and potentially leading to projects being non-viable altogether.[clix]

For cement decarbonization, this challenge is particularly pronounced in the context of CCUS projects, which can require substantial buildout of infrastructure (including pipelines), are perceived as allowing continued use of fossil fuels, and may come with additional environmental impacts that have to be abated. [45]

Solution 6: Implement robust community benefits plans and agreements that are responsive to public concerns, mitigate potential harms, and ensure accountability.

Community benefits agreements (CBA) are signed between developers and community groups that negotiate community support for a project in return for benefits from the developer.[clx] CBA negotiations are avenues for developers to engage with communities to understand how their project can meet with their goals while ensuring that community needs are met. These CBAs can incorporate mechanisms designed to mitigate the impacts from project development that the community is concerned about. Selected examples include requiring the usage of state-of-the-art scrubbers for facilities that may come with air pollution concerns, investments in local infrastructure, job training and local hiring requirements, and implementation of GHG reduction programs.

45 Discussed in detail in the Carbon Management Liftoff report.

Chapter 5: Metrics and milestones

The DOE will track two types of key performance indicators to understand the progress needed for successful decarbonization of the cement sector.

- **Leading indicators** are signs to evaluate the present status of technology readiness, market adoption readiness, and penetration of key technologies.
- **Lagging indicators** are retroactive verification of the successful or unsuccessful scaling and adopting of decarbonizing technologies (e.g., evaluations of progress toward net-zero targets).

The indicators outlined below can be used to track industry milestones and evaluate decarbonization progress. These metrics allow the integrated tracking of leading and lagging indicators, which can be updated and shared regularly. These milestones do not represent DOE targets but are important progress markers to create confidence across the ecosystem.

'Track'	Leading indicators / milestones	Lagging indicators / milestones
Overall	• Total investment in low-carbon cement	• Volume of low-carbon cement produced • Emissions intensity per tonne of cement industry-wide
Coordinated procurement model to unlock demand-pull across tracks	• Common methodology and standards for embodied carbon in cement and concrete (e.g., standard LCA methodology, EPD template) established and accepted by governments and the private sector • 'Library' of EPDs for low-carbon cement and concrete products established and made widely available • Commitments by large government and private-sector customers to buy low-carbon materials	• Share of government-driven cement procurement covered by low-carbon materials standards • Overall emissions intensity of government-purchased cement and concrete • Share of private-sector cement procurement covered by low-carbon materials standards
Clinker substitution, energy efficiency, and alternative fuels	• Successful demonstrations of LC3-type and ternary blends in key applications (e.g., road and highway pavings) by 2025 • Adoption or planned adoption of LC3-type and ternary blends by all 50 state DOTs	• Clinker factor (clinker share of cement mix by weight) industry-wide • Energy efficiency improvement relative to baseline • Alternative fuels share of industry energy consumption

CCUS	• 3–5 commercial-scale demonstrations by 2030, including demonstration of alternative capture technologies • Project finance model for CCUS established by 2030	• CCUS retrofits of existing plants, integration into new-build plants, associated capital formation
Alternative production methods	• 3–5 commercial-scale demonstrations by 2030 • Demonstrated technological success at commercial scale by 2030 • Initial cost reductions from FOAK to NOAK by 2030, consistent with commercial competitiveness with traditional production and CCUS • Products accepted under existing standards and adopted by large customers • Project finance model for greenfield deployments established by 2030	• Number of greenfield plant builds with alternative production methods and associated capital formation
Alternative binder chemistries	• Entry into the approval process and approval by industry standards organizations (timing will vary by material based on current TRL)	• Market share, starting in non-structural applications

Appendices

Appendix A: Modeling assumptions for Track A measures – clinker substitution, alternative fuels, and efficiency measures

Appendix A.1: Abatement potential and economic impact

Representative decarbonization pathways were modeled to estimate the economic and emissions impact of the currently deployable measures considered under Track A (clinker substitution, alternative fuels, and efficiency measures). Three representative scenarios were developed in consultation with industry experts to estimate the abatement potential and economic opportunity associated with deployment of these levers:

- **2030 Scenario 1: Moderate deployment.** More moderate but still ambitious deployment of key technologies, representing a slightly more ambitious set of deployment targets than the 2021 PCA roadmap. Modeling suggests the measures considered could abate 23% of sector emissions by 2030 if deployed consistent with Scenario 1 (22% from economically positive measures).
- **2030 Scenario 2: Aggressive deployment**. More aggressive deployment of key technologies by 2030, assuming targeted interventions can unlock accelerated scale-up. It presents a particularly ambitious, but achievable set of high-end targets. Modeling suggests the measures considered could abate 36% of sector emissions by 2030 if deployed consistent with Scenario 2 (32% from economically positive measures).
- **2050 Scenario**: Potential scale-up of key technologies in 2050. Modeling suggests the measures considered could abate up to 48% of sector emissions by 2050 if deployed consistent with this scenario (44% from economically positive measures).

These scenarios should be taken as directional estimates and are intended to be representative of feasible outcomes, not predictive or prescriptive. The report focuses on Scenario 2 to highlight an achievable upper-bound potential for deployable technologies, but, as noted in the report, industry is not presently on track to deploy at this scale. Significant intervention will be required to achieve deployment milestones consistent with Scenario 2.

Scenarios may overstate the potential impact from clinker substitution because they do not account for use of SCMs already taking place at ready-mix concrete plants, rather than cement plants. Scenarios may also overstate deployment potential of biomass fuels, which are in limited supply (discussed in Chapter 3).

Detailed assumptions and outputs are given for each scenario below. Note: for clinker substitution in all scenarios, "proportion in cement" refers to a weighted average across all modeled U.S. cement production, not the share of the material in a specific cement blend or at an individual cement plant.

2030 Scenario 1: Moderate deployment

Key assumptions

Category	Assumption	Unit	Value	Source / notes
Energy Efficiency	Assumed energy efficiency improvement in 2030	% energy savings	5%	Assumed based on modernizations, upgrades, machine learning, and artificial intelligence. PCA 2021 US roadmap (p. 30) documents planned decrease of 5-7%.
Energy Efficiency	Implied impact on emissions in 2030	% reduction in CO2e per tonne cement	5%	Assumed 5% reduction in energy emissions based on 5% energy emissions decrease.
Alternative fuels - biomass	Assumed % of total fuel needs in 2030	% of total fuel need	5%	PCA 2021 US roadmap (p 29) documents aspiration to use biomass based alternative fuels for ~5% of fuel mix in 2030. Used assumption given high costs and supply constraints.
Alternative fuels - waste	Assumed % of total fuel needs in 2030	% of total fuel need	35%	PCA 2021 US roadmap (p 29) documents aspiration to use waste based alternative fuels for ~25% of fuel mix in 2030. Assumed 10% higher share in scenario given cost effectiveness of waste based alternative fuels.
Alternative fuels - waste	Tires as share of overall fuel mix 2030	%	20%	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; Scrapped tires are the largest share of waste-based fuels. Page 44 of report models 15% share. Assumed maximum substitution rate from same report of 20% due zinc and sulfur content.
Alternative fuels - waste	Waste plastic as share of overall fuel mix 2030	%	10%	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; limited to substitution rate of 10% due to chlorine content.
Alternative fuels - waste	Other alternative fuel waste streams as share of overall fuel mix 2030	%	5%	Calculation done to bridge. Other waste streams will be required given scrapped tires and waste plastics have maximum substitution limits.
Clinker substitution	Clinker proportion in cement 2030	%	75%	PCA 2021 US roadmap (p 35) documents a planned decrease to 0.75 clinker to cement ratio by 2050 with 0.85 target for 2030. Have assumed 0.75 target for 2030 could be met by using calcined clay and shifts of fly ash from concrete to cement production step.
Clinker substitution	Limestone proportion in cement 2030	%	10%	In-line with ASTM C595 range of 5-15%; exact ratio most likely given industry implementation/feasibility (Industry expert input).
Clinker substitution	Gypsum proportion in cement 2030	%	5%	Assumed share does not change in 2030.
Clinker substitution	Other proportion in cement 2030	%	0.7%	Assumed share does not change in 2030.
Clinker substitution	Calcined clay proportion in cement 2030	%	6%	Assumed high replacement of clinker with calcined clay given abundance of material and favorable economics
Clinker substitution	Fly ash proportion to be mixed with clinker in 2030	%	2.0%	ASTM C595 range; exact ratio most likely given industry implementation/feasibility (Industry expert input)

Clinker substitution	GGBFS proportion to be mixed with clinker in 2030	%	0.5%	Assumed no change given limited additional volumes likely going forward
Clinker substitution	Natural pozzolans proportion to be mixed with clinker in 2030	%	1.0%	Assumed small increase in share of pozzolans used given low emissions intensity, though generally not used in US. Concrete Innovations - NRMCA

Scenario outputs

	2030		
Levers	**Abatement cost (USD/tCO2)**	**Abatement potential (MtCO2)**	**% of BAU emissions abated**
Energy efficiency	-31.1	1.5	2%
Alternative fuels - biomass	161.5	0.6	1%
Alternative fuels - waste	-4.6	6.4	7%
Clinker substitution	-54.0	11.4	13%

Annual savings to industry ($M)	(691.59)

2030 Scenario 2: Aggressive deployment

Key assumptions

Category	Assumption	Unit	Value	Source / notes
Energy Efficiency	Assumed energy efficiency improvement in 2030	% energy savings	5%	Assumed based on modernizations, upgrades, machine learning, and artificial intelligence. PCA 2021 US roadmap (p. 30) documents planned decrease of 5-7%
Energy Efficiency	Implied impact on emissions in 2030	% reduction in CO2e per tonne cement	5%	Assumed 5% reduction in energy emissions based on 5% energy emissions decrease
Alternative fuels - biomass	Assumed % of total fuel needs in 2030	% of total fuel need	15%	PCA 2021 US roadmap (p 29) documents aspiration to use biomass based alternative fuels for ~5% of fuel mix in 2030. Used assumption given high costs and supply constraints
Alternative fuels - waste	Assumed % of total fuel needs in 2030	% of total fuel need	35%	PCA 2021 US roadmap (p 29) documents aspiration to use waste based alternative fuels for ~25% of fuel mix in 2030. Assumed 10% higher share in scenario given cost effectiveness of waste based alternative fuels
Alternative fuels - waste	Tires as share of overall fuel mix 2030	%	20%	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; Scrapped tires are the largest share of waste-based fuels. Page 44 of report models 15% share. Assumed maximum substitution rate from same report of 20% due zinc and sulfur content.
Alternative fuels - waste	Waste plastic as share of overall fuel mix 2030	%	10%	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; limited to substitution rate of 10% due to chlorine content

Alternative fuels - waste	Other alternative fuel waste streams as share of overall fuel mix 2030	%	5%	Calculation done to bridge. Other waste streams will be required given scrapped tires and waste plastics have maximum substitution limits
Clinker substitution	Clinker proportion in cement 2030	%	65%	PCA 2021 US roadmap (p 35) documents a planned decrease to 0.75 clinker to cement ratio by 2050 with 0.85 target for 2030. Have assumed 0.65 target for 2030 could be met by using calcined clay and shifts of fly ash from concrete to cement production step
Clinker substitution	Limestone proportion in cement 2030	%	15.0%	High-end of range of ASTM C595 range; exact ratio most likely given industry implementation/feasibility (Industry expert input)
Clinker substitution	Gypsum proportion in cement 2030	%	5%	Assumed share does not change in 2030
Clinker substitution	Other proportion in cement 2030	%	0.5%	Assumed share does not change in 2030
Clinker substitution	Calcined clay proportion in cement 2030	%	9%	Assumed high replacement of clinker with calcined clay given abundance of material and favorable economics
Clinker substitution	Fly ash proportion to be mixed with clinker in 2030	%	3.0%	ASTM C595 range; exact ratio most likely given industry implementation/feasibility (Industry expert input). Assumed slight increase in fly-ash given economics and emission intensity, though potentially limited supply going forward
Clinker substitution	GGBFS proportion to be mixed with clinker in 2030	%	0.5%	Assumed no change given limited additional volumes likely going forward
Clinker substitution	Natural pozzolans proportion to be mixed with clinker in 2030	%	1.5%	Assumed small increase in share of pozzolans used given low emissions intensity, though generally not used in US. Concrete Innovations - NRMCA

Scenario outputs

	2030		
Levers	**Abatement cost (USD/tCO2)**	**Abatement potential (MtCO2)**	**% of BAU emissions abated**
Energy efficiency	(31.1)	1.5	2%
Alternative fuels - biomass	34.2	3.4	4%
Alternative fuels - waste	(4.6)	6.4	7%
Clinker substitution	(59.4)	19.7	23%

Annual savings to industry ($M)	(1,246.47)

2050 Scenario

Key assumptions

Category	Assumption	Unit	Value	Source / notes
Energy Efficiency	Assumed energy efficiency improvement 2050	% energy savings	20%	Assumed based on modernizations, upgrades, machine learning, and artificial intelligence. PCA 2021 US roadmap (p. 30) documents planned decrease of 20-30%
Energy Efficiency	Implied impact on emissions in 2050	% reduction in CO2e per tonne cement	20%	Assumed based on modernizations, upgrades, machine learning, and artificial intelligence. PCA 2021 US roadmap (p. 30) documents planned decrease of 20-30%
Alternative fuels - biomass	Assumed % of total fuel needs in 2050	% of total fuel need	20%	PCA 2021 US roadmap (p 29) documents aspiration to use biomass based alternative fuels for ~15% of fuel mix in 2050. Assumed slightly higher %
Alternative fuels - waste	Assumed % of total fuel needs in 2050	% of total fuel need	50%	PCA 2021 US roadmap (p 29) documents aspiration to use biomass based alternative fuels for ~45% of fuel mix in 2050. Assumed slightly higher %
Alternative fuels - waste	Tires as share of overall fuel mix 2050	%	20%	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; Scrapped tires are the largest share of waste-based fuels. Page 44 of report models 15% share. Assumed maximum substitution rate from same report of 20% due zinc and sulfur content.
Alternative fuels - waste	Waste plastic as share of overall fuel mix 2050	%	10%	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; limited to substitution rate of 10% due to chlorine content
Alternative fuels - waste	Other alternative fuel waste streams as share of overall fuel mix 2050	%	20%	Calculation done to bridge. Other waste streams will be required given scrapped tires and waste plastics have maximium substitution limits
Clinker substitution	% clinker in 2050	% of total cement	60%	PCA 2021 US roadmap (p 35) documents a planned decrease to 0.75 clinker to cement ratio by 2050. Have assumed 0.6 target for 2050 could be met by using limestone, calcined clay, natural pozzolans, and innovative SCMs
Clinker substitution	Limestone proportion in cement 2050	%	13%	In-line with ASTM C595 range of 5-15%; exact ratio most likely given industry implementation/feasibility (Industry expert input)
Clinker substitution	Gypsum proportion in cement 2050	%	5%	Assumed share does not change in 2050
Clinker substitution	Other proportion in cement 2050	%	5.00%	Assumed mix of concrete waste and innovative SCMs.
Clinker substitution	Calcined clay proportion in cement 2050	%	15%	Assumed high replacement of clinker with calcined clay given abundance of material and favorable economics

Clinker substitution	Pozzolans proportion in cement 2050	%	2%	Assumed small increase in share of pozzolans used given low emissions intensity, though generally not used in US. Concrete Innovations - NRMCA

Scenario outputs

	2050		
Levers	**Abatement cost (USD/tCO2)**	**Abatement potential (MtCO2)**	**% of BAU emissions abated**
Energy efficiency	(31.1)	6.7	7%
Alternative fuels - biomass	30.1	4.5	5%
Alternative fuels - waste	(9.7)	10.1	10%
Clinker substitution	(59.9)	26.0	27%

Annual savings to industry ($M)	(1,866.14)

Appendix A.2: Economic deep dives

Economic deep dives were performed for select clinker substitutes and alternative fuels. General assumptions used for these deep dives are given below:

Category	Assumption	Unit	Value	Source / notes
Baseline - all	Capacity	Million tonnes/yr	1.5	Assumption, consistent with NETL 2023 modeling
Baseline - all	Utilization	Percent	100%	Assumption
Baseline - all	Lifecycle	years	20.0	Assumption
Baseline - alternative fuels	Coal cost	$/tonne of coal	60.0	US EIA
Baseline - alternative fuels	Coal emission intensity	kg CO2/ GJ of coal	96.1	Fuel CO2 emissions factors IPCC guidelines table 2.3; GCCA GNR 2020 for fuel mix
Baseline - alternative fuels	Coal heat value	GJ/tonne of coal	28.5	https://www3.epa.gov/ttnchie1/ap42/ch01/final/c01s01.pdf. Took mid-point of values between 24,400 and 32,500. Also: https://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx
Baseline - alternative fuels	Fossil fuel share of combined fuel	%	85%	GNR (2020 average)
Baseline - alternative fuels	Coal % of fossil fuel share	%	68%	GNR (2020 average)
Baseline - alternative fuels	Coal % of combined fuel	%	58%	Calculated
Baseline - alternative fuels	Petcoke % of fossil fuel share	%	21%	GNR (2020 average)
Baseline - alternative fuels	Petcoke % of combined fuel	%	18%	Calculated
Baseline - alternative fuels	Petcoke cost	$/ tonne of petcoke	163.8	Average 2022 price USGC Argus fob USGC 6.5pc sulphur coke index
Baseline - alternative fuels	Petcoke heat value	GJ/tonne petcoke	32.0	GNR (2020 average)
Baseline - alternative fuels	Petcoke emissions intensity	kgCO2/ GJ of petcoke	97.5	Fuel CO2 emissions factors IPCC guidelines table 2.3; GCCA GNR 2020 for fuel mix
Baseline - alternative fuels	Natural gas cost	$/GJ of natural gas	7.23	Calculated from below
Baseline - alternative fuels	Natural gas cost	$/MMBTU of natural gas	7.6	EIA average US industrial price 2022 - https://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PIN_DMcf_a.htm
Baseline - alternative fuels	MMBtu to GJ conversion	GJ	1.1	
Baseline - alternative fuels	Natural gas % of fossil fuel share	%	11%	GNR (2020 average)

Baseline - alternative fuels	Natural gas % of combined fuel	%	9%	Calculated
Baseline - alternative fuels	Natural gas emission intensity	kg CO2/ GJ natural gas	56.1	Fuel CO2 emissions factors IPCC guidelines table 2.3; GCCA GNR 2020 for fuel mix.
Baseline - alternative fuels	Natural gas heat value	GJ/ton	48.5	midpoint, https://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx
Baseline - alternative fuels	Secondary fuel % of combined fuel	%	15%	GNR (2020 average).
Baseline - alternative fuels	Secondary fuel heat value	*GJ/tonne of fuel*	35.0	Assumption similar to waste tire.
Baseline - alternative fuels	Secondary fuel emission intensity	kg CO2/ tonne of fuel	85.0	Waste (tire) as proxy.
Baseline - alternative fuels	Secondary fuel cost	$/tonne of fuel	30.0	Assumption - 50% of coal value
Baseline - alternative fuels	Combined fuel emission intensity	kgCO2/ tonne combined fuel	90.9	Calculated
Baseline - SCM	Clinker proportion in cement	%	95%	GNR (2020 average)
Baseline - alternative fuels	Heat consumption	kJ per kg clinker	3875.0	GNR (2020 average)
Baseline - alternative fuels	Heat consumption	GJ per t cement	3.7	Calculation from above
Baseline - SCM	All in clinker cost	$/tonne of clinker	69.3	Clinker cost calculated in separate tab (see back up bottoms up build up). Adding in heuristic to account for additional processing etc., involved with clinker in cement production
Baseline - SCM	Clinker to cement heuristic	%	0.8	Heuristic to convert clinker cost to cost of clinker used for cement due to additional energy requirements
Baseline - SCM	Gypsum proportion in cement	%	5%	GNR (2020 average)
Baseline - SCM	Clinker emission intensity	kg CO2/ tonne of cement	790.0	Bottom-up analysis + median range from EPA, https://www.epa.gov/system/files/documents/2021-10/cement-carbon-intensities-fact-sheet.pdf
Baseline - SCM	Clinker emission intensity	kg CO2/ tonne of clinker	828.0	Chemical emissions from clinker (525kgCO2/tonne clinker) + fuel needed for kiln (303 kgCO2/tonne clinker)
Baseline - SCM	Gypsum emission intensity	kgCO2/ tonne gypsum	0.0	Assumed purchase of gypsum, resulting in scope 3 emissions
Baseline - SCM	Gypsum cost	$/tonne of cement	1.0	18 USD in 2018 for uncalcined gypsum in the US (Source: USGS); assuming 20 USD in 2020 and 5% per tonne of cement

Baseline - SCM	Gypsum cost	$/ tonne of gypsum	20.0	Calculated using gypsum proportion in cement
Alternative fuels - biomass	Capex for kiln bypass, storage	$M/plant	10.0	Industry expert input assumption, assumes multi-fuel burner (common in the US); equity financed 100%
Alternative fuels - biomass	Capex amortization period	years	2.0	To fully implement (equity financed 100%)
Alternative fuels - biomass	Biomass cost	$/tonne of wood	41.0	Average of Jan, Feb, March 2023 cost per tonne of manufacturing densified biomass products (EIA); https://www.eia.gov/biofuels/biomass/#table_data
Alternative fuels - biomass	Biomass heat value	GJ/tonne of wood	14.7	https://ens.dk/sites/ens.dk/files/Statistik/metode_traeaffald.pdf
Alternative fuels - biomass	Biomass emission intensity	kg CO2/ GJ of biomass	0.0	Industry expert input
Alternative fuels - biomass	Biomass % of total fuel	%	60%	Maximum potential given lower heat value of wood (combined fuel heat value should be 22GJ/ton+
Alternative fuels - waste	Capex for kiln bypass, storage	$M/plant	10.0	Industry expert input assumption, assumes multi-fuel burner (common in the US)
Alternative fuels - waste	Capex amortization period	years	2.0	To fully implement (equity financed)
Alternative fuels - waste	Tire cost	$/tonne tire chips	15.3	Calculated from below
Alternative fuels - waste	Opex cost of co-processing scrap tires	$/tonne of tires	10.0	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; Assumed tires are pre-processed off-site before arriving at plant. Page 43 provides co-processing estimates from (GIZ/Holcim 2020, ICF 2017). Used low-end of estimates
Alternative fuels - waste	Cost of energy from tires	$/GJ	5.3	Proxy cost for sourcing tires (nominal cost of energy x heat value)
Alternative fuels - waste	Nominal price of energy from tires	$/GJ	0.2	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; Page 44 provides estimates ($0.15/GJ, US tires 2021). Used mid-points of estimates and calculated $/tonne by multiplying by heat value
Alternative fuels - waste	Capex cost of scrap tires	$M/plant	1.0	Emissions Impacts of Alternative Fuels Combustion in the Cement Industry (2023) report; Page 43 provides pre- and co-processing estimates from (GIZ/Holcim 2020, ICF 2017). Used low end of estimate. Assumed pre-processing occurs offsite before arriving at plant
Alternative fuels - waste	Tire emission intensity	kg CO2/ GJ tire	85.0	https://www.eia.gov/environment/emissions/co2_vol_mass.php
Alternative fuels - waste	Tire heat value	GJ/kg tire	35.0	Used midpoint from Thermogravimetric and Kinetic Analysis of Co-Combustion of Waste Tires and Coal Blends (2021), https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7931440/#:~:text=The%20calorific%20value%20of%20the,coal%20and%20other%20solid%20fuels

Alternative fuels - waste	Tire % of total fuel	%	20%	GCCA GNR (2020). 30% waste based alternative fuels from tires, 6% from plastics, and 5% from waste oils and the rest from a mix. Have assumed tires, plastics and waste oils comprise total and scaled each %
Alternative fuels - waste	Other waste cost	$/tonne other waste	11.38	Calculated using average of tire and waste plastics
Alternative fuels - waste	Capex cost for other waste	$M/plant	1.3	Calculated using average capex of waste tire and waste plastics
Alternative fuels - waste	Other waste emission intensity	kg CO2/ GJ other waste	80.0	Calculated using average of tire and waste plastics
Alternative fuels - waste	Other waste heat value	GJ/kg other waste	35.0	Calculated using average of tire and waste plastics
Alternative fuels - waste	Other waste % of total fuel	%	70%	GCCA GNR (2020). 30% waste based alternative fuels from tires, 6% from plastics, and 5% from waste oils and the rest from a mix. Have assumed tires, plastics and waste oils comprise total and scaled each %
Alternative fuels - waste	Waste plastic cost	$/tonne waste plastic	7.5	Calculated from below
Alternative fuels - waste	Cost of co-processing waste plastics	$/tonne of waste plastic	7.5	IFC 2017 report: INCREASING THE USE OF ALTERNATIVE FUELS AT CEMENT PLANTS: INTERNATIONAL BEST PRACTICE. Page 67 appendix table. Used mid-points of estimates for small facility given 5% production. Assumed pre-processing occurs offsite before arriving at plant
Alternative fuels - waste	Cost of energy from waste plastics	$/GJ waste plastic	0.0	Assumed cement plants receive this for free instead of being paid for it to go to landfills.
Alternative fuels - waste	Capex cost of waste plastics	$M/plant	1.6	IFC 2017 report: INCREASING THE USE OF ALTERNATIVE FUELS AT CEMENT PLANTS: INTERNATIONAL BEST PRACTICE. Page 67 appendix table. Used mid-points of estimates for small facility given 5% production. Assumed pre-processing occurs offsite before arriving at plant.
Alternative fuels - waste	Waste plastic emission intensity	kg CO2/ GJ waste plastic	75.00	Morgan Stanley Research Report - Cement decarbonization (Energy efficiency and alternative fuels)
Alternative fuels - waste	Waste plastic heat value	GJ/kg waste plastic	35.0	ECRA 2016; EPA 2020b
Alternative fuels - waste	Waste plastic % of total fuel	%	10%	GCCA GNR (2020). 30% waste based alternative fuels from tires, 6% from plastics, and 5% from waste oils and the rest from a mix. Have assumed tires, plastics and waste oils comprise total and scaled each %
Clinker substitutes - Fly ash	Fly ash to be mixed with clinker	%	30%	ASTM C595 range; exact ratio most likely given industry implementation/feasibility (Industry expert input)
Clinker substitutes - Fly ash	Emission intensity fly ash	kg CO2/ tonne fly ash	0.1	MPA Fact Sheet 18, CO2e of UK cement, additions and cementitious material
Clinker substitutes - Fly ash	Fly ash cost	$/tonne fly ash	45.0	Industry expert input

Clinker substitutes - all	Proportion gypsum to be mixed with clinker	%	5%	Global Cement and Concrete Association, 2020 (US numbers)
Clinker substitutes - all	Gypsum cost	$/ tonne of gypsum	20.0	Calculated using gypsum proportion in cement and USGS $/tonne gypsum
Clinker substitutes - GGBFS	Proportion to be mixed with clinker	%	0.5	ASTM C595 range; exact ratio most likely given industry implementation/feasibility (Industry expert input)
Clinker substitutes - GGBFS	Emission intensity	kg CO2/ tonne GGBFS	79.6	MPA Fact Sheet 18, CO2e of UK cement, additions and cementitious material, assuming transport costs and grinding at plant)
Clinker substitutes - GGBFS	GGBFS cost	$/tonne GGBFS	55.0	https://www.chemanalyst.com/Pricing-data/ggbfs-1307#services
Clinker substitutes - natural pozzolans	Natural pozzolan cost	$/tonne pozzolans	11.0	USGS Mineral Yearbook 2022 Summary, construction sand cost as a proxy (incl extraction, transport and margin of the seller)
Clinker substitutes - natural pozzolans	Proportion to be mixed with clinker	%	0.3	ASTM C595 range; exact ratio most likely given industry implementation/feasibility (Industry expert input)
Clinker substitutes - natural pozzolans	Emission intensity	kg CO2/ tonne pozzolans	0.1	Similar to fly ash, assuming no additional treatment needed
Clinker substitutes - calcined clay	CC % to be mixed with clinker	%	30%	ASTM C595 range; exact ratio most likely given industry implementation/feasibility (Industry expert input)
Clinker substitutes - calcined clay	Proportion limestone to be mixed with clinker	%	15%	Industry expert input
Clinker substitutes - calcined clay	CC emission intensity	kg CO2/ tonne of CC	187.3	Refer to emission intensity of CC tab
Clinker substitutes - calcined clay	Limestone emission intensity	kgCO2/ tonne limestone	8.0	Limestone fines, MPA Fact sheet 18 CO2e of UK cement, additions and cementitious material
Clinker substitutes - calcined clay	Calcined clay cost	$/tonne CC	7.0	Assumed similar raw material opex cost as limestone given similarity of processes (e.g., extraction) and abundance as clay
Clinker substitutes - calcined clay	Limestone cost	$/ tonne of limestone	7.0	USGS Mineral Yearbook Summary for crushed stone (incl. limestone), selling price (2022) at $14/ton, deducting transportation costs (50 km at 0.1 USD/t/km = 5 USD) and margin of 20% gives proxy for production costs at ~$7/ tonne
Clinker substitutes - calcined clay	Capex for additional rotary kiln	$M/plant	6.6	Financial Attractiveness of LC3, K. Scrivener, A. Dekeukelaere, F. Avet, L. Grimmeissen (assuming rotary kiln at plant at capacity, no available one for use given US demand. Assuming rotary kiln instead of flash calciner, given current commercial availability constraint of latter

Clinker substitutes - calcined clay	Capex for silo from other types of cement	$M/plant	8.0	Industry expert input and cross-checked with press clippings on project announcements for cement silos (e.g., Tokyo Cement announced a Cement terminal with 3 cement silos costing total of $12M in 2021). https://www.globalcement.com/news/item/13440-tokyo-cement-commissions-colombo-cement-terminal. Assumed higher cost per terminal
Clinker substitutes - calcined clay	Capex for raw material storage	$M/plant	1.0	Industry expert input
Clinker substitutes - calcined clay	Amortization period	years	2.0	
Clinker substitutes - calcined clay	Heat consumption of calcined clay	TJ/ton	2.2	THAA Cemtech 2021
Clinker substitutes - calcined clay	Electricity for grinding	kwh/ton	20.0	Loesche
Clinker substitutes - calcined clay	Electricity	USD/MWh	73	US EIA
Clinker substitutes - calcined clay	Maintenance cost for new equipment	$/tonne calcined clay	5	Assumption: 50% of cement maintenance costs
Clinker substitutes - calcined clay	Labor costs for new equipment	$/tonne calcined clay	12.13	65% of labor costs for baseline (lower production volume)
Baseline - all	WACC	%	10%	Assumption

Appendix A.3: Representative efficiency measures

The modeling exercise assumes adoption of representative efficiency measures outlined below, identified based on input from industry experts:[46]

Initiative	Electrical saving (kwh/t)	Thermal saving (GJ/t)	Investing cost ($/t)
Efficient transport systems (elevator instead of air conveyor)	3.4	0	3
Process control vertical mill	1.55	0	1
Energy management and process control	4	0	1
High efficiency classifiers in cement (product) mill	3.95	0	2
Improved grinding media in ball mills	4	0	0.5
High efficiency motors (applying variable speed drive)	3	0	0.2
Efficient fans with variable speed drive	7	0	1.3
Optimization of compressed air systems	3	0	0.2
Efficient lighting (led)	0.3	0	0.3
Production of low alkali cement	0	0.44	0
Convert to reciprocating grate cooler	-3	0.27	2.9
Kiln combustion system improvements	0	0.3	1
Optimize heat recovery/upgrade clinker cooler	-2	0.105	0.2
Seal replacement in the kiln process	0	0.011	0.1
Low pressure drop cyclones	2.55	0	3
Efficient kiln drives motors	0	0	0.3
Improved refractories material	0	0.5	0.3
Kiln shell heat loss reduction	6.1	0.365	0.3
Adjustable speed drive for kiln fan	0.1	0	0.2
Selecting raw material with lower friction coefficient	0	0	0.1
Selecting raw material with lower humidity	0.1	0.1	0.1
Selecting raw material with lower dimension	0	0.1	0.1

46 Energy savings and costs estimated based on Mokhtar, Nasooti (2020), "A decision support tool for cement industry to select energy efficiency measures." *Energy Strategy Reviews*.

Appendix B: CCUS economics assumptions

Figures for carbon capture are based on NETL 2023 modeling for 95% capture at a preheater/precalciner kiln fueled with coal and coke, using a CANSOLV amine-best post-combustion system, on a 1.5 MTPA cement plant.[47] Capital costs are adjusted to reflect a 12-year payback period using capital recovery factors from the Energy Futures Initiative.[48] Transportation and storage costs of ~$10–40 per tonne of captured CO2 are assumed, consistent with Carbon Management Liftoff report.[49]

This estimate does not include other owner's costs such as pre-production costs associated with start-up and performance evaluation and inventory of chemicals and spare parts for ongoing operations. These costs are assumed to be limited and not to materially alter project economics.

Detailed calculations for storage (CCS) and utilization (CCU) cases are provided in Table B.1 and Table B.2, respectively.

47 Hughes, Sydney, et al. (2023, Apr.). Analysis of Carbon Capture Retrofits for Cement Plants. National Energy Technology Laboratory. Microsoft Word - 17-4-1-2_Cement Plant Retrofit Capture_DFR_Rev7.docx (doe.gov).

48 Brown, Jeffrey D., et al. (2023, Feb.). Turning CCS projects in heavy industry and power into blue chip financial investments. Energy Futures Initiative. EFI - CCS Report (energyfuturesinitiative.org).

49 Fahs, Ramsey, et al. (2023, Apr.). Pathways to Commercial Liftoff: Carbon Management. U.S. Department of Energy. Pathways to Commercial Liftoff: Carbon Management (energy.gov).

Table B.1: CCS economics

Assumption	Low	High	Sources / notes
Case used	CM95-B	CM95-B	PH/PC kiln with coal/coke
Capital costs			
Total capex, $M	$ 544,376,000.00	$ 544,376,000.00	From NETL study for CM95-B
Capital recovery factor	0.11	0.13	CRF used by EFI for 12-year payback (compare to NETL CRF for 30-year payback of 4.63%)
Amortized capital cost, $ p.a.	$ 59,881,360.00	$ 70,768,880.00	
Operating costs			
Fixed O&M, $ p.a.	$16,575,809.00	$16,575,809.00	From NETL study for CM95-B
Variable O&M, $ p.a.	$11,335,656.00	$11,335,656.00	From NETL study for CM95-B
Total O&M, $ p.a.	$27,911,465.00	$27,911,465.00	From NETL study for CM95-B
Fuel + Power, $ p.a.	$33,649,342.00	$33,649,342.00	From NETL study for CM95-B
OPEX, $ p.a.	$61,560,807.00	$61,560,807.00	From NETL study for CM95-B
Total cost p.a.	$121,442,167.00	$132,329,687.00	
CO2 captured, tonnes p.a.	1,104,478	1,104,478	Assumes 95% capture of 1,162,608 tonnes CO2 emitted from kiln p.a. for dry PH/PC kiln
Cement output, tonnes p.a.	1,500,000	1,500,000	Assumption of NETL study

Model outputs		
Cost of capture, $ / tonne of CO2	$109.95	$119.81
Total capital cost, $ / tonne of CO2	$ 54.22	$ 64.07
Total O&M cost, $ / tonne of CO2	$25.27	$25.27
Fuel + power cost, $ / tonne of CO2	$30.47	$30.47
Cost of capture, $ / tonne of cement	$80.96	$88.22
Total capital cost, $ / tonne of cement	$ 39.92	$ 47.18
Total O&M cost, $ / tonne of cement	$18.61	$18.61
Fuel + power cost, $ / tonne of cement	$22.43	$22.43
With T&S		
Transport & storage cost, $ per tonne of CO2	$10	$40
Transport & storage cost, $ per tonne of cement	$7.36	$29.45
Cost of capture + T&S, $ / tonne of CO2	$119.95	$159.81
Cost of capture + T&S, $ / tonne of cement	$88.32	$117.67
Premium on $130 base price per tonne of cement	68%	91%
Net of 45Q		
45Q, $ per tonne of CO2	$85	$85
45Q, $ per tonne of cement	$62.59	$62.59
Cost of capture + T&S net of 45Q, $ / tonne of CO2	$34.95	$74.81
Cost of capture + T&S net of 45Q, $ / tonne of cement	$25.74	$55.09
Premium on $130 base price per tonne of cement	20%	42%
Cost reduction to breakeven with 45Q	29%	47%
Offtake commitment contract sizing		
Offtake commitment p.a.	$38,606,317.00	$82,628,177.00
Total offtake commitment (12 yrs)	$463,275,804.00	$991,538,124.00

Table B.2: CCU economics

Assumption	Low	High	Sources / notes
Case used	CM95-B	CM95-B	PH/PC kiln with coal/coke
Capital costs			
Total capex, $M	$ 544,376,000.00	$ 544,376,000.00	From NETL study for CM95-B
Capital recovery factor	0.11	0.13	CRF used by EFI for 12-year payback (compare to NETL CRF for 30-year payback of 4.63%)
Amortized capital cost, $ p.a.	$ 59,881,360.00	$ 70,768,880.00	
Operating costs			
Fixed O&M, $ p.a.	$16,575,809.00	$16,575,809.00	From NETL study for CM95-B
Variable O&M, $ p.a.	$11,335,656.00	$11,335,656.00	From NETL study for CM95-B
Total O&M, $ p.a.	$27,911,465.00	$27,911,465.00	From NETL study for CM95-B
Fuel + Power, $ p.a.	$33,649,342.00	$33,649,342.00	From NETL study for CM95-B
OPEX, $ p.a.	$61,560,807.00	$61,560,807.00	From NETL study for CM95-B
Total cost p.a.	$121,442,167.00	$132,329,687.00	
CO2 captured, tonnes p.a.	1,104,478	1,104,478	Assumes 95% capture of 1,162,608 tonnes CO2 emitted from kiln p.a. for dry PH/PC kiln
Cement output, tonnes p.a.	1,500,000	1,500,000	Assumption of NETL study

Model outputs		
Cost of capture, $ / tonne of CO2	$109.95	$119.81
Total capital cost, $ / tonne of CO2	$ 54.22	$ 64.07
Total O&M cost, $ / tonne of CO2	$25.27	$25.27
Fuel + power cost, $ / tonne of CO2	$30.47	$30.47
Cost of capture, $ / tonne of cement	$80.96	$88.22
Total capital cost, $ / tonne of cement	$ 39.92	$ 47.18
Total O&M cost, $ / tonne of cement	$18.61	$18.61
Fuel + power cost, $ / tonne of cement	$22.43	$22.43
With T&S		
Transport & storage cost, $ per tonne of CO2	$10	$40
Transport & storage cost, $ per tonne of cement	$7.36	$29.45
Cost of capture + T&S, $ / tonne of CO2	$119.95	$159.81
Cost of capture + T&S, $ / tonne of cement	$88.32	$117.67
Premium on $130 base price per tonne of cement	68%	91%
Net of 45Q		
45Q, $ per tonne of CO2	$85	$85
45Q, $ per tonne of cement	$62.59	$62.59
Cost of capture + T&S net of 45Q, $ / tonne of CO2	$34.95	$74.81
Cost of capture + T&S net of 45Q, $ / tonne of cement	$25.74	$55.09
Premium on $130 base price per tonne of cement	20%	42%
Cost reduction to breakeven with 45Q	29%	47%
Offtake commitment contract sizing		
Offtake commitment p.a.	$38,606,317.00	$82,628,177.00
Total offtake commitment (12 yrs)	$463,275,804.00	$991,538,124.00

Appendix C: Capital formation sizing

The capital formation opportunity for cement is estimated roughly and directionally for 2030, 2050, and cumulatively, assuming two kinds of deployments:

- Scale-up of currently deployable measures (e.g., clinker substitution and alternative fuels) at all plants excluding grinding-only plants, including active plants and potential additions by 2030 and 2050. [50, 51] Efficiency measures are not included because of data limitations.
- Scale-up of CCUS and alternative production measures—assumed to have roughly the same CAPEX requirement based on industry conversations—at all plants excluding grinding-only plants, including currently active plants and potential additions by 2030 and 2050.

For the 2030 horizon, it is assumed that currently deployable measures are fielded at the entire footprint of cement plants, while CCUS and alternative production methods see ~3–5 initial deployments each, consistent with their Pathways to Liftoff.

For the 2050 horizon, it is assumed that the remaining plant sites (those not covered by demonstrations) see deployment either of a CCUS retrofit or greenfield build using an alternative production method or potentially a novel chemistry.

This approach may overstate CAPEX requirements in two ways:

- It assumes CAPEX for all measures will remain roughly consistent regardless of plant size. For CCUS, greenfield plants, and in many cases of the currently deployable measures, CAPEX is unlikely to vary with plant size, given that similar equipment is required regardless of production capacity. In other cases, plant size may have more of an impact on CAPEX.
- It does not assume CAPEX reductions from FOAK to NOAK.

A detailed CAPEX buildup is given in Table C.

50 Excluding five current plants that are grinding-only.

51 Number of potential new-build plants is estimated by calculating the 1.5 MTPA plants required to meet incremental demand by 2030 and 2050. Potential new-build plant capacity may be overstated if incremental demand is met with latent capacity at existing plants rather than new construction.

Table C: Capital formation sizing

	By 2030		Incremental by 2050		Cumulative by 2050	
	Low	High	Low	High	Low	High
Est. plant footprint						
Baseline plant footprint, excluding 5 grinding-only plants, #	93	93	93	93		
Baseline production (2022), Mtpa	95	95	95	95		
Production in outyear (2030 or 2050), Mtpa	109	109	124	124		
Est. capacity per new build plant, Mtpa	1.5	1.5	1.5	1.5		
Implied new build plants, #	9	9	19	19		
Implied total plants, excluding grinding-only, #	102	102	112	112		
CAPITAL FORMATION						
Demonstrations						
<u>CCUS</u>						
Assumed CCUS demo CAPEX, $M	500	1,000	500	1,000		
CCUS demos, #	3	5				
Total CCUS demo CAPEX	1,500	5,000				
<u>Alt production methods</u>						
Assumed alt production method demo CAPEX, $M	500	1,000	500	1,000		
Alt production method demos, #	3	5				
Total alt production method demo CAPEX	1,500	5,000				
Total demo CAPEX	3,000	10,000			3,000	10,000
Deployments						
<u>Currently deployable measures</u>						
Alternative fuels and efficiency CAPEX per plant, $M	10	10	10	10		
Clinker substitution CAPEX per plant, $M	16	60	16	60		
Total CAPEX per plant, $M	26	70	26	70		
Total plants deployed, #	102	102	10	10		
Total CAPEX for deployment	2,652	7,140	260	700	2,912	7,840
<u>CCUS or alt production methods</u>						
CAPEX per deployment, $M	500	1,000	500	1,000		
Total plants deployed, # (excluding demos)	0	0	106	102		
Total CAPEX for deployment	0	0	53,000	102,000	53,000	102,000
TOTAL CAPITAL FORMATION						
Incremental by outyear, $M	5,652	17,140	53,260	102,700	58,912	119,840

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