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Climate Knowledge Initiative

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Decarbonizing Cement

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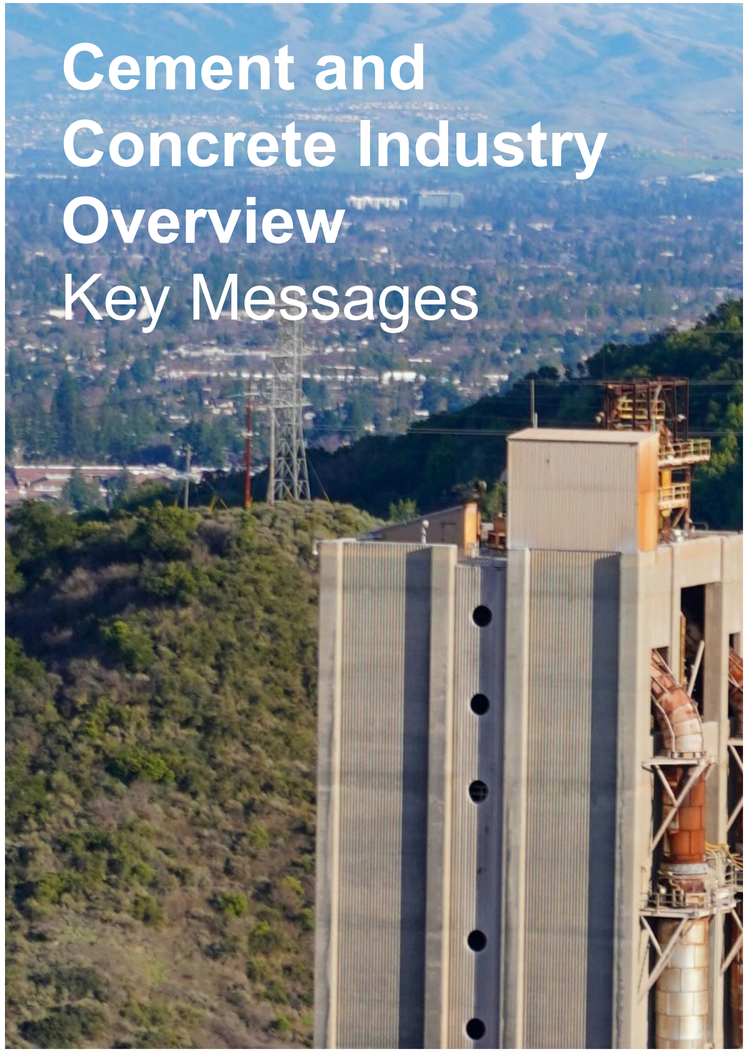
Cement and Concrete Industry Overview



Cement and Concrete Industry Overview
Key Messages

The global cement industry accounts for **~5% to 8% of global CO_2 emissions**, with partial decoupling from production growth.

- Global cement emissions have **more than doubled since 2000** (from 0.7 Gt in 2000 to 1.6 Gt in 2023), while cement output rose ~2.6x.
- **Emissions intensity declined ~15% since 2000** (CAGR -0.7%), reflecting efficiency gains.
- China's share of production fell below 50% in 2023 for the first time in 15 years, while India and Sub-Saharan Africa will drive future demand growth (+42% and +77% by 2030).

Clinker production drives **80% to 90% of cement manufacturing emissions, dominated by calcination and thermal heat:**

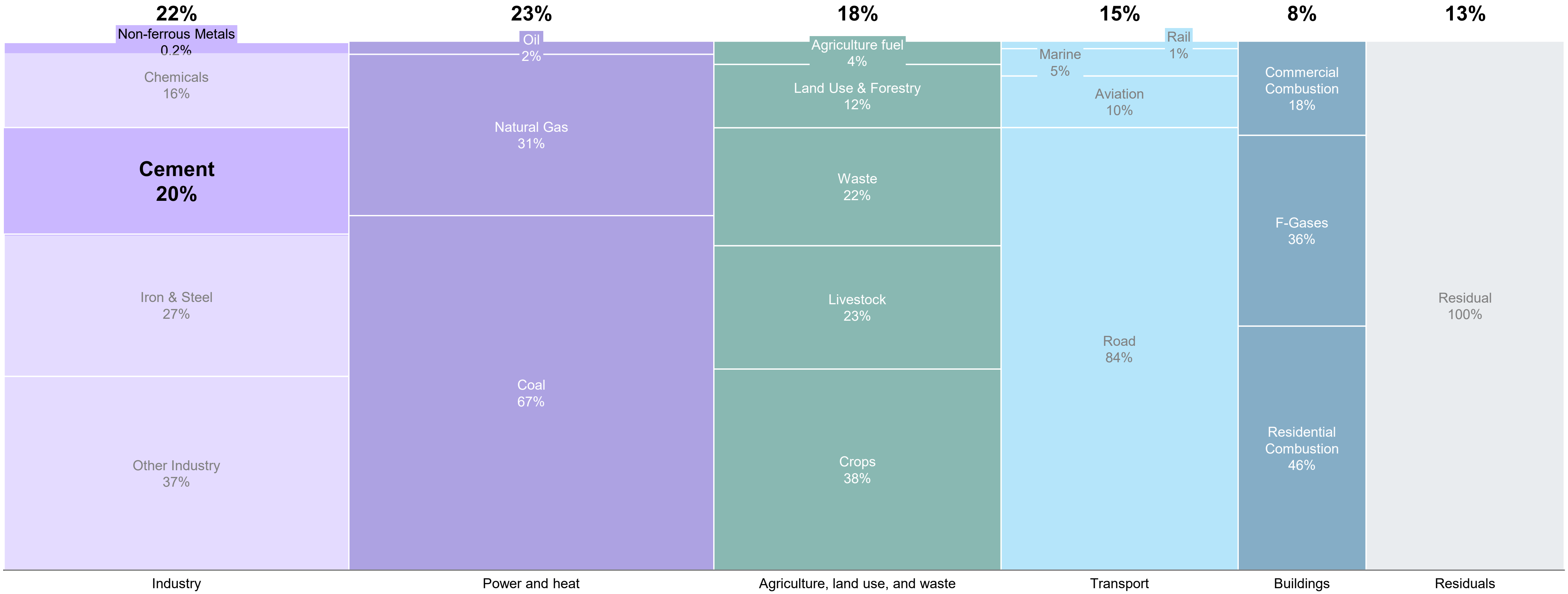
- ~50% to 60% from limestone calcination and ~30% to 40% from fossil fuel combustion for kiln heat.
- Dry-kiln systems have improved **energy efficiency by ~45%** compared to wet kilns; over 80% of global production now uses dry kilns.
- Further optimization of kilns and adoption of low-carbon heat sources are key to addressing process emissions.

The industry has been able to **reduce emissions intensity by ~17% since the beginning of the century** through energy efficiency levers and reduction of the clinker-to-cement ratio.

- The average **clinker-to-cement ratio in the U.S. is 0.88** (880 kilograms of clinker per metric ton of cement) as of 2022.
- The **global average clinker-to-cement ratio is 0.76**, achieved by the increasing share of supplementary cementitious materials (SCMs).
- Portland-limestone cement (PLC) blends up to 15% uncalcined limestone, reducing lifecycle CO_2 by ~10%.
- Aging kilns and rising demand present an opportunity to **replace or retrofit 15% to 25% of plants over 80 years old, further accelerating reductions in emissions intensity.**

Cement and concrete production account for ~5% to 8% of global CO_2 emissions, mostly scope 1

CO_2e emissions in 2025: ~55 billion tons



Source: Network for Greening the Financial System, NGFS 2025 climate scenarios (2024).
Credit: Theo Moers, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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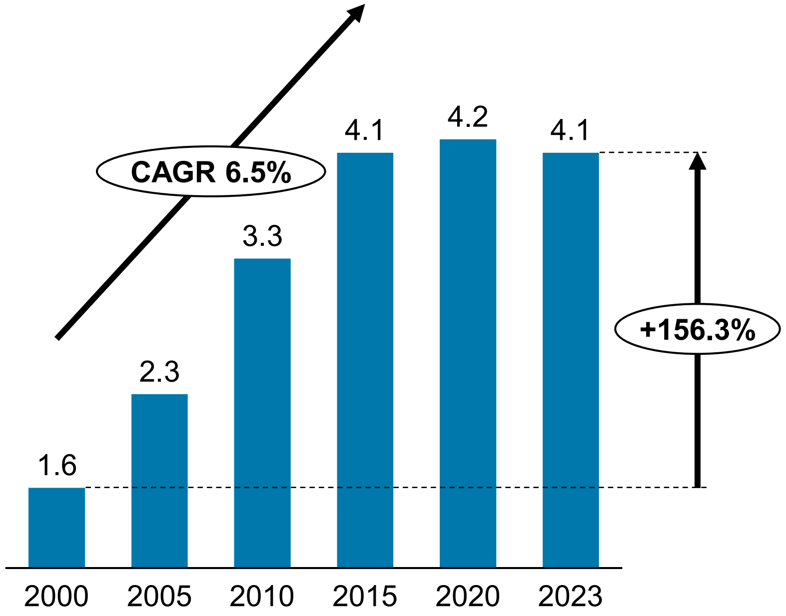
Cement manufacturing emissions are up ~2.2x since 2000, with partial decoupling from production growth (up ~2.6x)

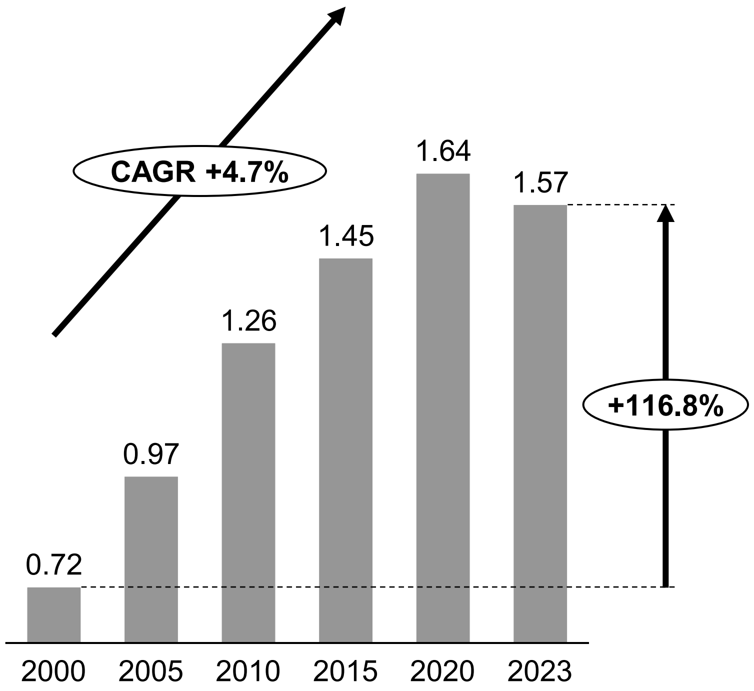
Cement production grew ~2.6x from 2000 to 2015, then stagnated

Global cement production, *billion tons*



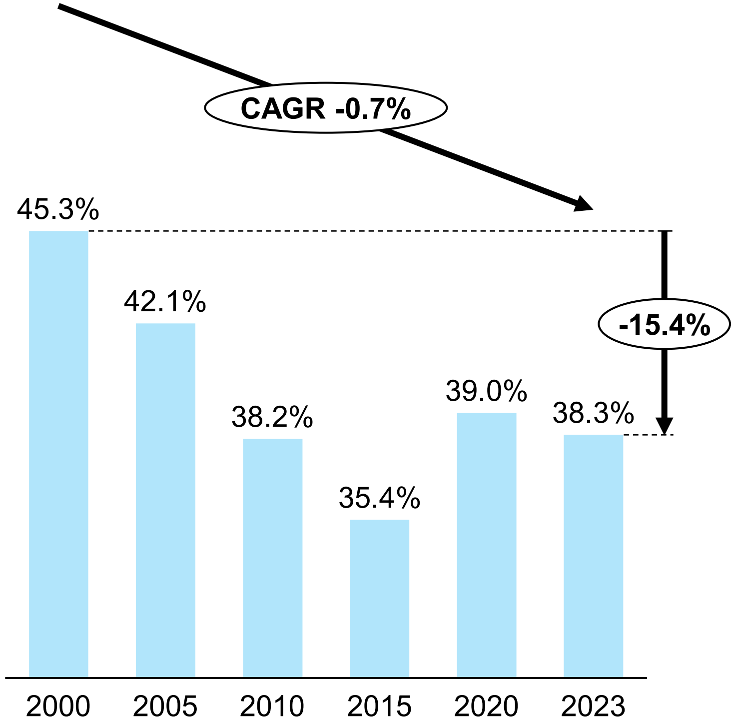
Cement emissions grew at a lower rate (~2.2x) than production (~2.6x)

Global cement manufacturing emissions, *$GtCO_2$*



Emissions-to-production ratio drop suggests efficiency improvements

Cement emissions-to-production ratio, *%*



Sources: Global Carbon Atlas, Carbon Emissions (2024); USGS, Mineral Commodity Summaries (2025).
Credit: Nicolas Herrera Isaza, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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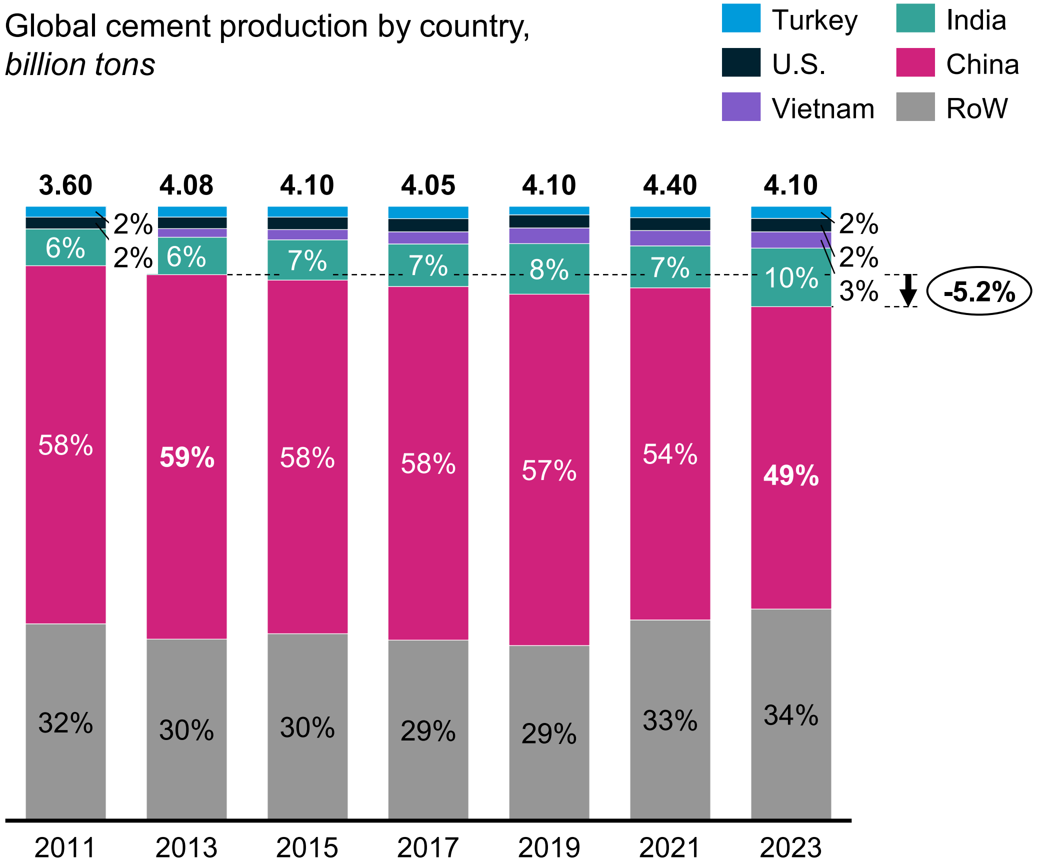
China has dominated cement production for the past decade, but share expected to decline while emerging markets' demand grows

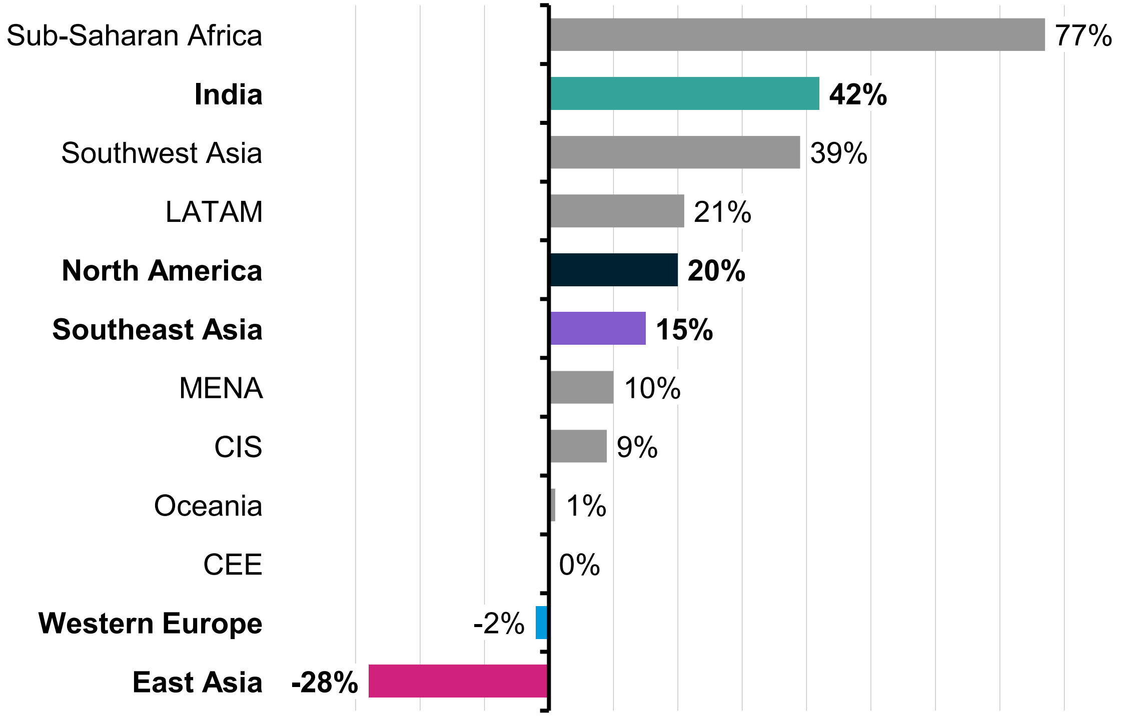
China's production share peaked in 2013, then dipped below 50% of global in 2023 for the first time in 15 years

Global cement production by country, *billion tons*



Demand from emerging markets, led by Sub-Saharan Africa and India, is expected to increase sharply

2030 cement demand growth outlook, *%*



Sources: USGS, Mineral Commodity Summaries (2025); World Cement Association, Industry Outlook (2024).
Credit: Nicolas Herrera Isaza, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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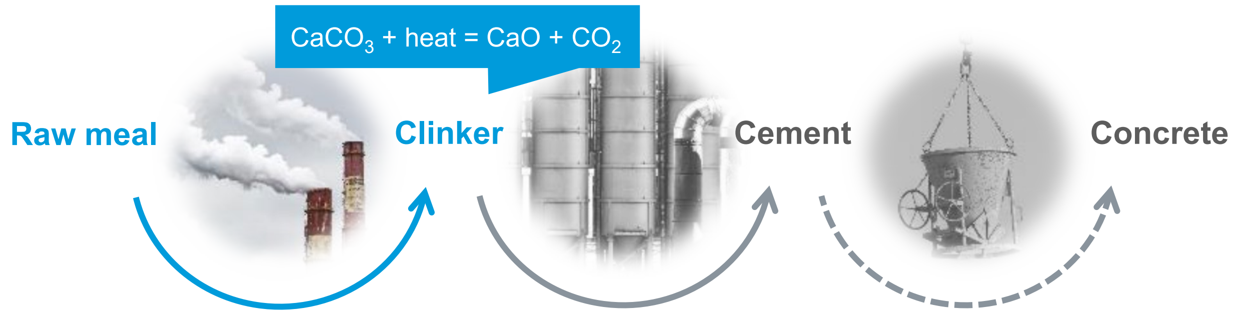
Clinker production is ~85% of cement emissions; dry-kiln adoption has led to significant efficiency gains

Clinker production is the first step in concrete production[1]



1 Preheat

- Vertical cyclones with exhaust gases from the kiln are heated at ~900°C.
- Raw meal of crushed limestone and other minerals go in.

2 Precalcining

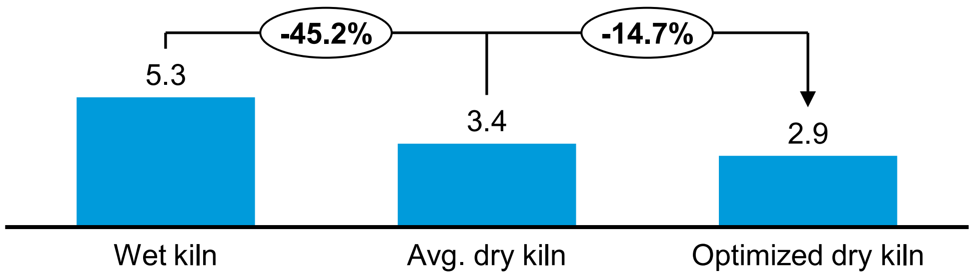
- Limestone is partially decomposed into lime in a combustion chamber before entering the kiln.

3 Melting clinker

- Precalcined meal enters the rotary kiln heated to 1,450°C with fossil fuels combustion.
- Clinker is produced.

Dry kilns have replaced wet kilns for clinker production

Kilns energy efficiency, *GJ/t clinker*



Observations

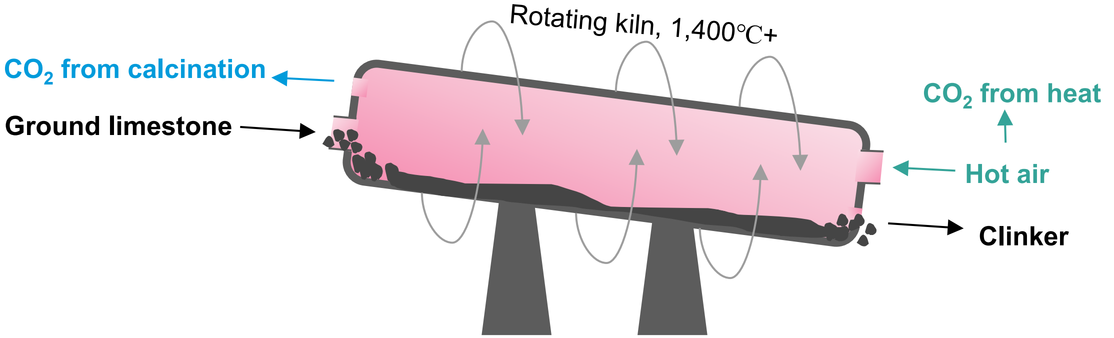
- Calcination of limestone and combustion of fuels used to bring limestone to the required temperature account for **~90% of clinked production emissions**.
- **The industry is rapidly shifting to adopt dry kilns**, with over 80% of global and 90% of European clinker production now using dry kilns. This shift reflects a clear willingness and capacity to change best practices to favor efficiency.
  - In dry kilns, raw materials are ground into a fine powder to form a raw meal; in wet kilns, raw materials are mixed with water to form a slurry.
  - The wet process is relatively **less energy efficient and more resource intensive**, with more energy required to evaporate the water in the slurry.

[1] The production process shown assumes dry-kiln processing, which has widely replaced wet-kiln processing globally.

Sources: Environmental Development, Energy conservation and emission reduction for cement (2022); Portland Cement Association (2024); CEMBUREAU, Cement manufacture fact sheet (2021); Mission Possible, Making net-zero concrete and cement possible (2023).

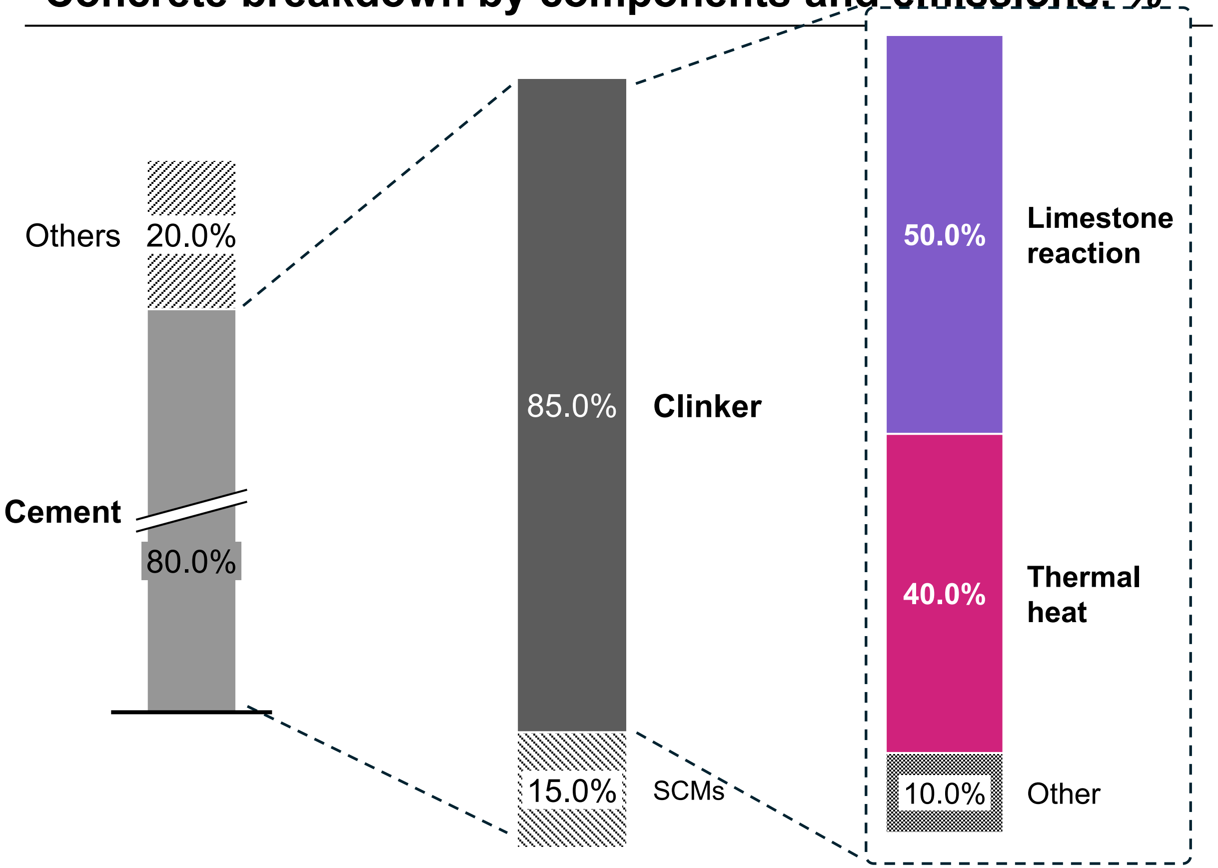
Clinker production accounts for over ~85% of cement emissions, of which ~50% are chemical and ~40% thermal

Dry-kiln clinker production process



$CaCO_3$ + heat → CaO + CO_2
(Limestone) (Lime)
↓
CO_2

Concrete breakdown by components and emissions, %



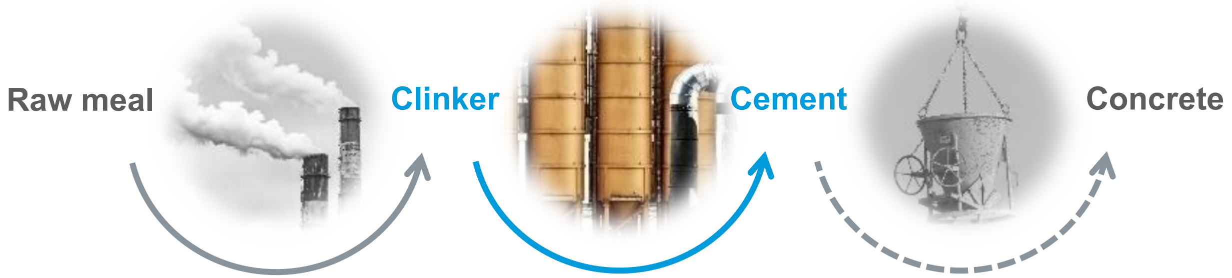
Observations

- Cement is just **15% of concrete mix**, yet it accounts for **~80% of the emissions.**
- Overall, **clinker accounts for ~65% to 70% of concrete emissions.**
- Addressing cement emissions, specifically those related to clinker production, **is key to mitigating climate change.**

Sources: World Resource Institute, U.S. cement emissions (2024); BBC News, Climate change: The massive CO2 emitter you may not know about (2018).
Credit: Nicolas Herrera Isaza, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

Clinker production ~85% of cement emissions; lower clinker-to-cement ratio can drive marginal emissions reductions

Clinker-to-cement production process[1]



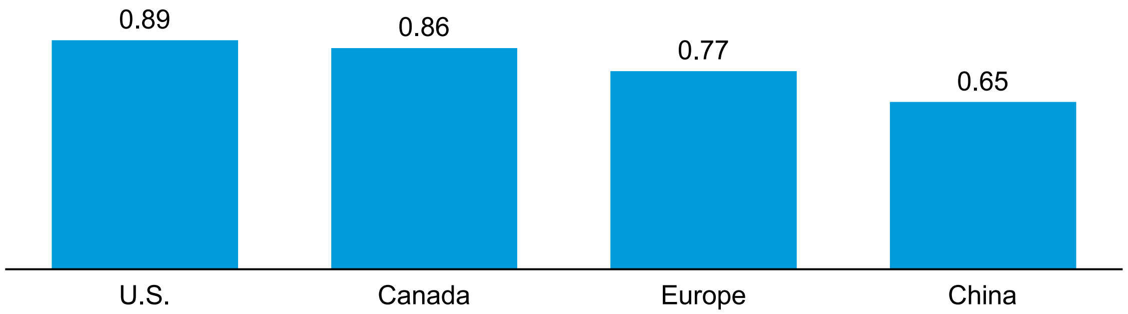
1 Cooling

- Hot clinker is rapidly cooled to 100°C with air blowers powered by electricity.

2 Grinding and blending

- Clinker is mixed with 4% to 5% gypsum.
- In some cases, it is mixed with other supplementary cementitious materials (SCMs) (e.g., slag, CCR, clay).
- The mixture is ground and blended into cement.

Clinker-to-cement ratios vary considerably by region



Observations

- Energy emissions from **cement grinding account for ~5% of the sector's emissions**.
- The higher clinker-to-cement ratio in the U.S. (0.88 versus 0.76 world average) is due to the U.S.'s use of a lower proportion of SCMs than other countries.
- Ordinary Portland cement (OPC) can contain up to 95% clinker.
- Blended cements, which partially replace clinker with SCMs, are a deployable and cost-effective technology, though they have struggled to gain market share.

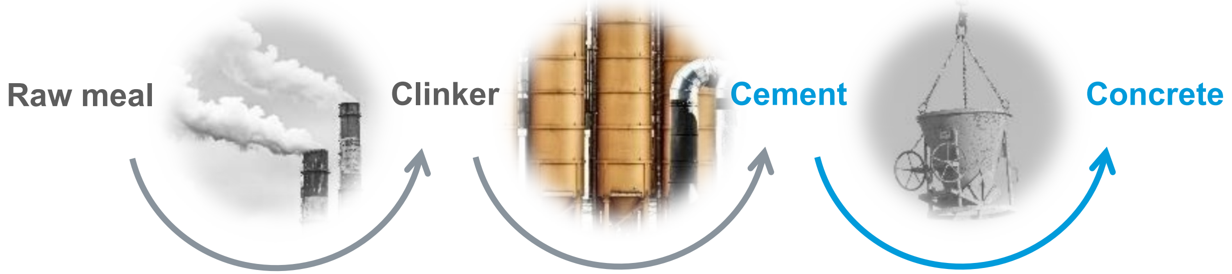
[1] The production process shown assumes dry-kiln processing, which has widely replaced wet-kiln processing globally.

Sources: CEMBUREAU, Net-zero roadmap (2024); Portland Cement Association (2024); CEMBUREAU, Cement manufacture fact sheet (2021); Mission Possible, Making net-zero concrete and cement possible (2023).

Credit: Nicolas Herrera Isaza, Jessica Cong, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

Concrete demand is expected to rise at a ~1.4% CAGR by 2050, driving an increase in absolute cement emissions

Clinker-to-concrete production process[1]



1 Cement + water

- Hydration is a chemical process triggered when these are mixed.
- It creates heat and a paste-like substance.

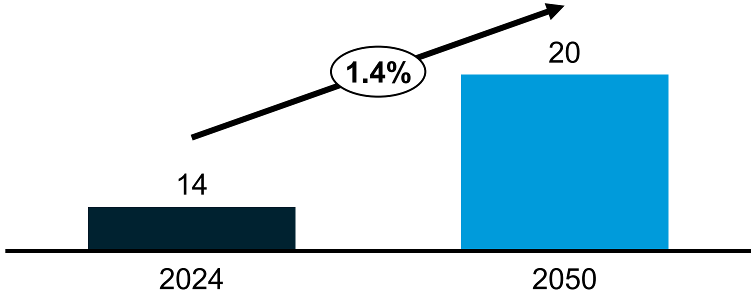
2 Add aggregates

- Sand and gravel are the ingredients that provide volume in the concrete mix.
- The sand fills in tiny spaces, while bigger pieces like gravel or crushed stone fill in larger gaps.

3 Extra additives

- Substances that act as accelerators, retarders, and air-entraining agents alter how the concrete works and improve its performance.

Concrete demand, *billion m^3*



Observations

- Cement is the binding component in concrete and can be used in less or more quantities depending on the strength needed for the end use.
  - Cement comprises 10 to 15% of concrete by weight.
- Energy emissions from concrete mixing and transportation account for ~5% of the sector's emissions.
- Concrete is usually made at or near a construction site (an average of 50 kilometers away).

[1] The production process shown assumes dry-kiln processing, which has widely replaced wet-kiln processing globally.

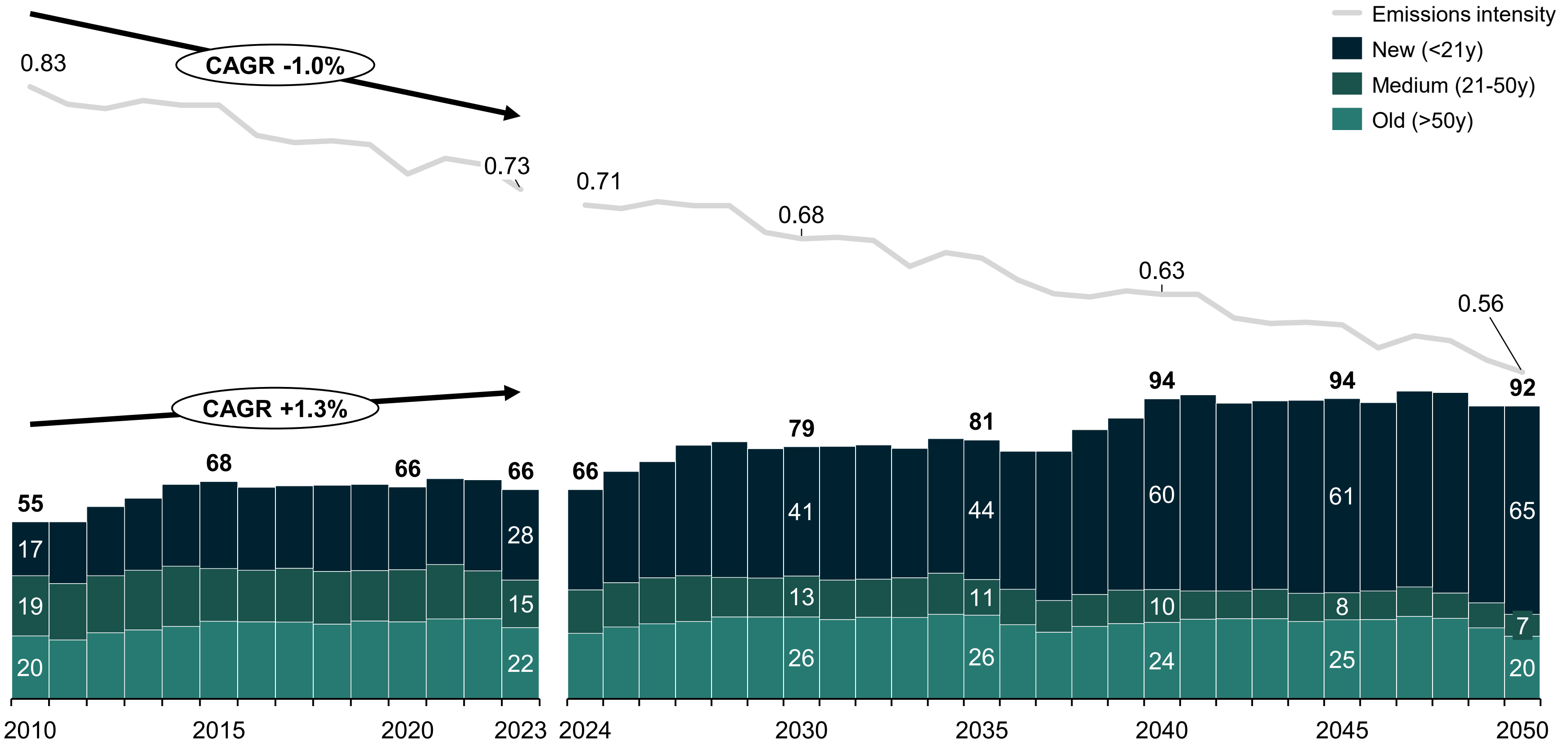
Sources: GCCA, Societal demand for cement and concrete (2024); Portland Cement Association, Roadmap to Carbon Neutrality (2021); CEMBUREAU, Cement manufacture fact sheet (2021); Mission Possible, Making net-zero cement possible (2023).

Credit: Nicolas Herrera Isaza, Jessica Cong, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

Intensity of U.S. cement emissions has been decreasing; aging plants provide further opportunities to improve efficiency

Efficiency gains have reduced the emissions intensity of U.S. cement production; emissions from new plants are projected to continue increasing due to growing demand

U.S. cement plants' emissions by plant age and overall emissions intensity, *$MtCO_2e$ and tCO_2e/t cement, 2010-2050*



Observations

- Due to new facilities and growing production, **emissions have continuously increased at an average 1.3% CAGR** since 2010.
- The rise of blended cements, fuel shifts from coal to natural gas, and deployment of **new and more efficient kilns** have reduced emissions intensity by 1% CAGR since 2010.
- **15% to 25% of plants** are 80+ years old and **could be replaced or retrofitted for higher efficiency**.
  - This shift could further reduce **emissions intensity**, which is **projected to reach 0.5 to 0.6 tCO2e/t by 2050**.
- A **significant gap** remains between the **current global average (~0.63)** and the IEA's net-zero by 2030 scenario of **0.45 emissions intensity**.

Sources: IEA, Cement (2022); EPA, Facility-level GHG emissions (2024); USGS, Mineral Commodity Summaries (2025).
Credit: Nicolas Herrera Isaza, Michelle Priscilla, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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Cement Decarbonization Technologies

Cement Decarbonization Technologies
Key Messages

Cement production remains **emission intensive**, demanding innovation beyond incremental efficiency.

- **~90%** of emissions stem from **limestone calcination and the high heat needed for clinker production.**

Deployable solutions can abate up to **~45% of emissions through efficiency and fuel and clinker substitution.**

- **Energy efficiency** measures are retrofit-ready, delivering **~10% to 15%** abatement at negative to low cost (~-\$50 /tCO_2).
- **Alternative fuels** such as bioenergy and waste-derived fuels can **replace up to 50% of fossil fuels.**
- **Substituting clinker with SCMs and LC3** can reduce emissions by **~15% to 40%**, with modest process adjustments and cost savings.

Emerging technologies can unlock deep decarbonization but require new infrastructure and capital investments.

- **Thermal batteries** can replace fossil fuel kilns with electric heat at up to 40% abatement, contingent on low-cost clean electricity.
- **Alternative feedstocks and electrochemical production** can eliminate up to **90% of process CO_2** but face **high CapEx and power intensity.**

Carbon capture, utilization, and storage (CCUS) serves as a transitional and complementary pathway to retrofit existing assets and reach near-zero emissions.

- **Carbon capture can mitigate up to 60% of emissions**, serving existing clinker plants and bioenergy systems.
- **High costs (\$60 to \$190/tCO_2) and limited storage access** constrain adoption, yet CCUS is critical for legacy plants and hard-to-abate clinker lines.

Cost-effective, deployable solutions can partially abate cement emissions; full decarbonization requires emerging technologies

○ R&D/Lab stage ◐ Pilot plant stage ◕ Ready for commercialization ● Mature and commercialized

	Energy efficiency		Clinker substitution		Alternative production technologies			Carbon capture
	Heat optimization	**Alternative fuels: Biomass/waste**	**Blended cement: Traditional SCMs**	**Blended cement: LC3**	**Thermal batteries[6]**	**Alternative feedstock**	**Electrochemical production**	**CCUS/CCS**
Description	Levers include: • Vertical mills or high-pressure grinding rolls • Kiln preheaters and improved insulation • Waste heat use • Digital process control	• Using biomass and waste as heat sources can lower thermal emissions: – Current kiln heat supply is fossil-fuel dominated (70% coal, 25% oil and gas)	• Supplementary cementitious materials (SCMs) • Can partially replace clinker in blended cements • Include CCR, steel furnace slag, and natural pozzolans	• Limestone calcined clay cement (LC3) • Blended cement that uses limestone and calcined clay • Can replace more clinker than traditional SCMs	• High-temperature thermal batteries, powered by cheap electricity, can replace fossil-fueled rotary kilns • Can be connected to the grid or powered by off-grid renewables	• Non-carbonate rocks can replace limestone as feedstock • Can avoid the chemical emissions of limestone calcination	• Electrochemistry can break down limestone instead of high-heat kilns • Combined with non-carbonate feedstock, it can fully decarbonize cement production	• Retrofitting plants with carbon capture can remove CO_2 released during clinker production • Captured CO_2 can serve as feedstock, fuels, or building materials
Addressed emissions	Thermal	Thermal	Thermal and chemical	Thermal and chemical	Thermal	Chemical	Thermal	Thermal and chemical
Limiting factor	CapEx	Feedstock availability and cost	Material availability and depletion	Retrofit and CapEx	New tech, CapEx, energy cost	New tech, CapEx	New tech, CapEx, energy cost	High CapEx & OpEx, infrastructure
TRL	●	●	●	● [5]	◐	◐	◐	◔
Abatement potential[1]	~9% (2030) ~19% (2050)	~4% (2030) ~27% (2050)	~12% (2030) ~39% (2050)	~8% (2030) ~32% (2050)	~4% (2030)[2] ~12% (2050)	~4% (2030) ~11% (2050)	~15-20% (2030)[2] ~70-80% (2050)	~19% (2030) ~69% (2050)[4]
Abatement cost, $/tCO_2e$	-46.3/39 (2030) -26.9/14 (2050)	-80/-40 (2030) -25.4/-8 (2050)	-97.7/- 35 (2030) -48.2/- 19 (2030)	-82.7/- 32.2 (2030) -33.2/-11.5 (2050)	159/414 (2030)[3] 37/132 (2050)	-44.2/9 (2030)[3] -15.4/2 (2050)	287/593.4 (2030)[3] 74/152 (2050)	167/364 (2030)[3] 46.3/101 (2050)

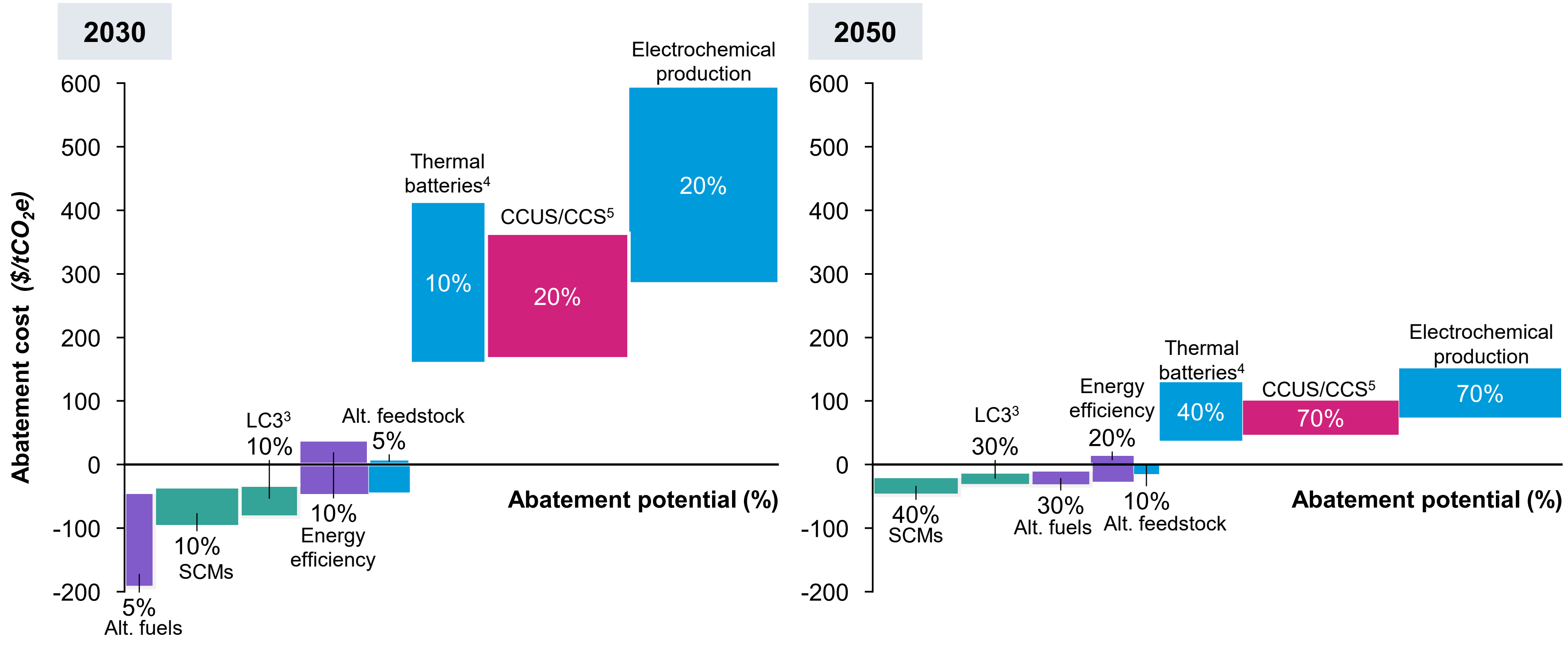
[1]Unconstrained theoretical abatement potential for a given ton of cement produced for each approach in isolation. [2]Assumes clean energy source. [3]Abatement cost of emerging technologies is based on estimates and has high uncertainty. [4]Reflects the approximate emissions gap after other measures, not a fixed technical limit. [5]Despite TRL9, market penetration remains minimal due to slow standards adoption, limited supply chain coordination, and conservative procurement practices. [6]Thermal batteries' abatement potential and cost are based on off-grid renewables.

Sources: DOE, Pathways to Commercial Liftoff Report (2023); Mission Possible, Net-zero concrete and cement (2023); CATF, Recasting the Future (2025); ACA, Roadmap to Carbon Neutrality (2021); GCCA, Concrete Future (2022); ClimateWorks Foundation, Low-carbon cement (2023); Energies, Alternative Fuels and Energy Efficiency in Cement (2023); International Journal of Greenhouse Gas Control, BioCCS in cement (2023); IEA, Bioenergy Annual Report (2022); RMI, The Business Case for LC3 (2024); Energy Innovation, Industrial Thermal Batteries (2023).

Credit: Camilo Avilés, Nicolas Herrera Isaza, Soraya Van Beek, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

Emerging technologies like thermal batteries, alternative feedstock, and electrochemistry are key to achieving full decarbonization

Abatement cost[1] vs. potential[2] for key decarbonization pathways by 2030 vs. 2050



Observations

- Currently deployable measures can deliver up to **30% emission reductions** through energy efficiency, alternative fuels, and blended cement (conventional SCMs and LC3).
- Alternative feedstock and electrochemical production can virtually eliminate cement production emissions but require significant technological advancements and transformational changes to production process.
- Thermal batteries' successful deployment depends heavily on **low-cost and low-carbon electricity.**
- Electrochemistry faces challenges including **high energy demand and competition for feedstock.**
- CCS costs vary widely depending on carbon **transportation and storage infrastructure.**

[1]Abatement cost of emerging technologies is based on estimates and has high uncertainty. [2]Abatement potential is calculated as unconstrained and theoretical for each approach in isolation. [3]Despite TRL 9, market penetration of LC3 remains low due to slow standards adoption, limited supply chain coordination, and conservative procurement practices. [4]Thermal batteries' abatement potential and cost are based on off-grid renewables; see slide 25 for grid power. [5]CCUS/CCS calculations reflect the approximate emissions gap after other measures, not a fixed technical limit.

Sources: DOE, Liftoff Report (2023); Mission Possible, Net-zero concrete and cement (2023); CATF, Recasting the Future (2025); ACA, Roadmap to Carbon Neutrality (2021); GCCA, Concrete Future (2022); ClimateWorks Foundation, Low-carbon cement (2023); Energies, Alternative Fuels and Energy Efficiency in Cement (2023); International Journal of Greenhouse Gas Control, BioCCS in cement (2023); IEA, Bioenergy Annual Report (2022); RMI, The Business Case for LC3 (2024); Energy Innovation, Industrial Thermal Batteries (2023).

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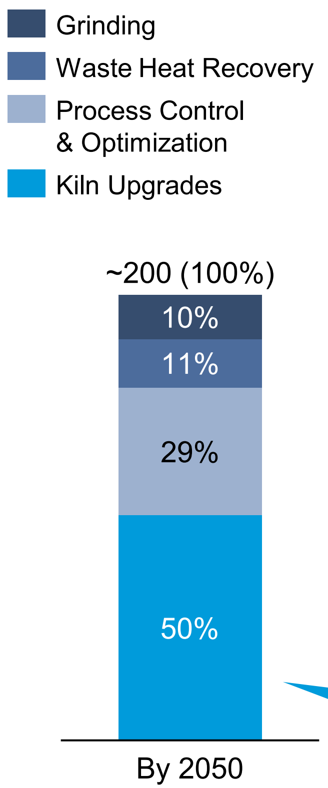
Currently deployable energy efficiency measures can cut ~10% to 15% of cement production emissions through plant retrofits

Process control and high-efficiency motors deliver largest abatement at easiest installation

Abatement potential of energy efficiency levers, 2023-50, *MtCO2/year*



Lever	Energy source	TRL 1-10	Retrofit or new	Ease of installation	Scalability	Co-benefits
Grinding optimization[1]	Electricity	9	Retrofit	**Medium** – major retrofit	High (all plant sizes)	Lower costs, finer product
Waste heat recovery[2]	Both	7-8	Retrofit	**Medium** – add-on unit	Medium (needs large scale)	On-site power, energy security
Process control & optimization[3]	Electricity	9	Retrofit	**High** – plug & play	Very high (all plants)	Stable ops, lower maintenance
Kiln upgrades[4]	Thermal	8-9	Retrofit and new	**Low** – very disruptive	High (large plants best)	Higher output, fuel flexibility

Abatement potential is expected to stay constant through 2050, as measures are already highly mature, with limited future efficiency gains. Impact is front loaded because potential can be realized now.

Observations

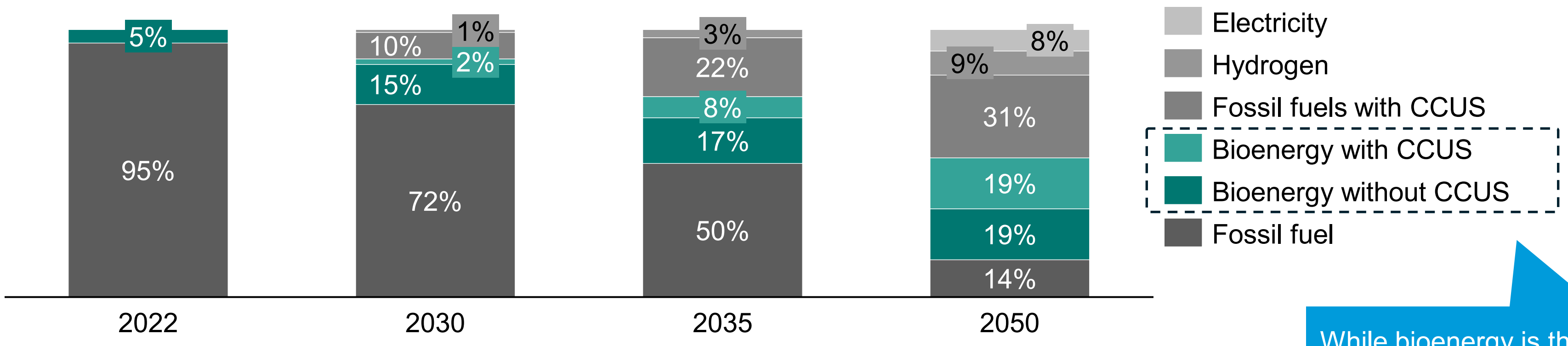
- Energy efficiency measures improve **how energy is consumed** rather than changing cement chemistry.
- The measures address **both electricity and thermal demand:** Grinding and motors reduce indirect emissions, while kiln upgrades and waste heat recovery cut fuel-related emissions.
- Most levers are retrofit-friendly, meaning most plants can implement them without rebuilding kilns, making them the **fastest abatement option** compared with SCMs or CCUS.

1) Grinding optimization: replacing ball mills with vertical roller mills or high-pressure grinding rolls; 2) Waste heat recovery systems: capture exhaust heat to generate power; 3) Process control and motor optimization: improve combustion stability and fine-tune equipment operation; 4) Kiln upgrades: modern preheaters, precalciners, and efficiency measures.

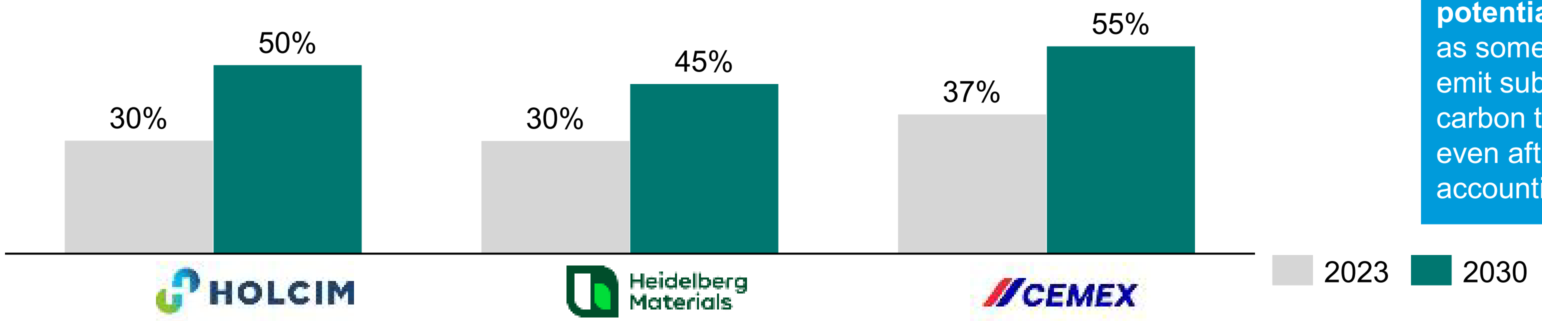
Sources: CSI/ECRA, Cement manufacturing: Trying to look ahead (2017); IEA, Technology Roadmap: Cement Industry (2018); MIT CEEPR, Cost-efficient pathways to decarbonizing cement (2023); Data Catalog, Global database of cement production assets (2025).

Share of bioenergy for heating kilns is expected to increase, as large producers set targets to shift away from fossil fuels

Replacing fossil fuels with bioenergy has an abatement potential of ~200 $MtCO_2$/year but varies widely by biomass type



Alternative fuels share targets, *2023-30, %*



While bioenergy is the main alternative fuel in cement, its **abatement potential varies widely**, as some **biomass** types emit substantially more carbon than fossil fuels even after biogenic accounting.

Observations

- **Coal dominates cement production fuel use at 70%**, followed by oil and natural gas at 24%. Alternative fuels (biomass, waste) account for just 5%.
- Switching to bioenergy fuels that are less carbon intensive than conventional fuels can **deliver reductions of ~200 $MtCO_2$, or 14% of the cumulative cement CO_2 emissions savings**, by 2050 under IEA 2°C — assuming 100% abatement of fuel emissions by bioenergy and an additional 20% process emissions abatement.
- Industry pilots are diversifying the alternative fuel mix: Heidelberg Materials is testing **hydrogen/ammonia** as fuel carriers to decarbonize kiln heat, while Cemex has produced **solar clinker with concentrated solar heat** (1,500°C+) and is scaling toward continuous industrial operation.

Sources: IEA, Cement NZE guide (2023); International Cement Review, China starts CCUS focus (2024); Heidelberg, First CCS facility in the cement industry (2024); Cemex, Our journey to net-zero (2024); Holcim, Our net-zero journey (2024); Global Efficiency Intelligence, Emissions impact of alternative fuels combustion in cement industry (2023).
Credit: Sho Tatsuno, Jessica Cong, Soraya Van Beek, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

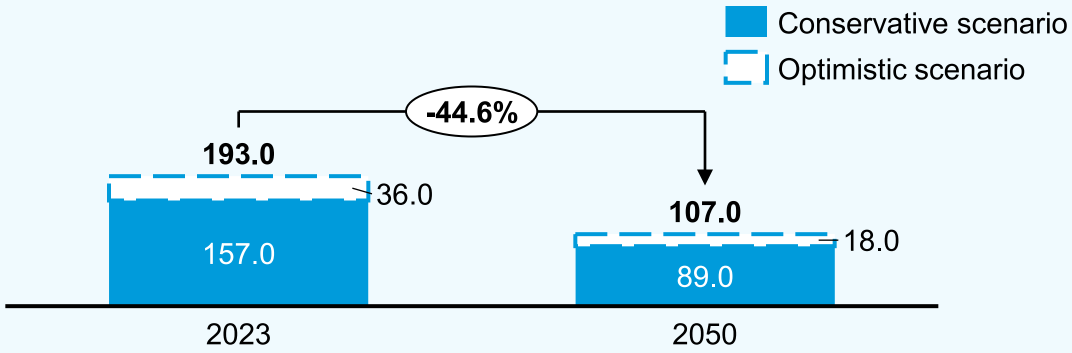
Cement kiln bioenergy deployment requires low CapEx, with abatement costs expected to drop ~20% to 45% by 2050

Bioenergy with CCS is capital intensive but offers potential negative emissions

Bioenergy with CCS

- Combines biofuels (incl. RDF/SRF, residues, energy crops) with CO_2 capture at kilns, **tackling both fuel and process emissions.**
- Costs are driven by biomass supply and CCS CapEx/OpEx (capture, compression, storage).
- Biomass use is commercial, but **CCS in cement is at pilot scale** (TRL ~6-7); storage infrastructure is at <1% of 2050 needs.
- Enables **near-complete or even net-negative thermal emissions**.

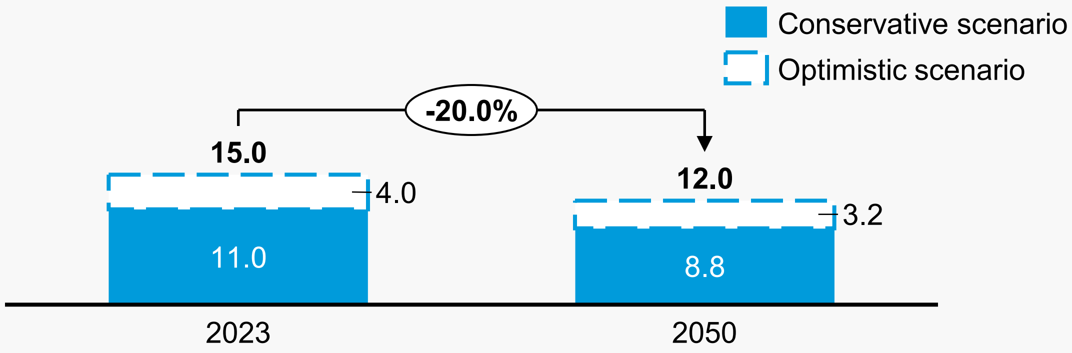
Abatement cost for bioenergy ***with*** CCS, 2023-50, $/tCO2



Bioenergy without CCS

- Main fuels: **RDF, SRF, and biomass residues** (wood waste, agricultural by-products, sewage sludge).
- **Already commercial** (TRL 8-9), widely used in Europe.
- Costs shaped by logistics, pre-treatment, and kiln retrofits; gate fees often make RDF/SRF very low-cost or even negative-cost fuels.
- Can **abate up to 100% of thermal emissions**.

Abatement cost for bioenergy ***without*** CCS, 2023-50, $/tCO2



Observations

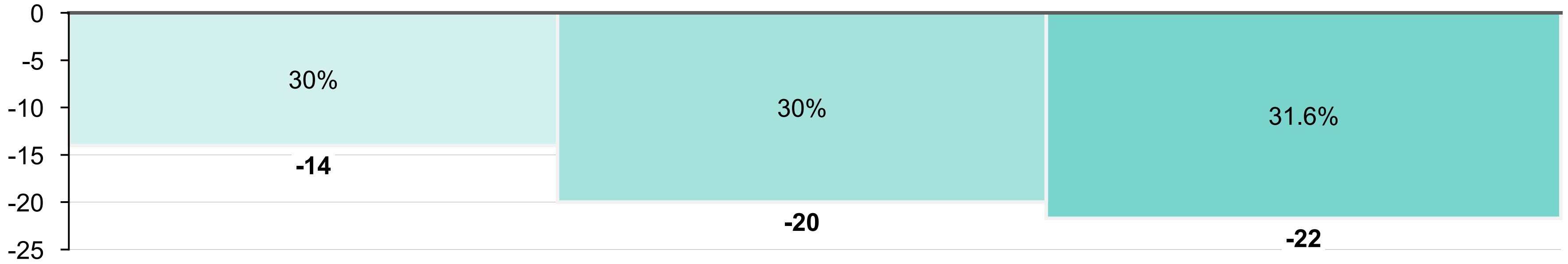
- **Bioenergy with CCS:** Current abatement costs are high (**≈\$157-\$193/tCO_2 in 2023**), but learning and scaling can reduce them by ~45% **by 2050 (≈\$89-\$107/tCO_2)**. Costs are dominated by CCS infrastructure (capture, compression, storage) rather than the fuel itself.
- **Bioenergy without CCS:** Costs are already very low (**≈\$11-\$15/tCO_2 in 2023**), driven by RDF/SRF gate fees and existing infrastructure. Modest improvements reduce costs further, by ~20% **to ≈\$9-\$12/tCO_2 by 2050**.
- **Policy dependence:** Deployment depends heavily on landfill and waste regulations (to supply RDF/SRF), carbon pricing (to value abatement), biomass sustainability rules, and public support for CO_2 transport and storage networks.

Sources: Energies, Alternative fuels and energy efficiency in cement (2023); International Journal of Greenhouse Gas Control, BioCCS in cement (2023); IEA, Bioenergy Annual Report (2022).
Credit: Soraya Van Beek, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

Blended cements partially replace clinker, reducing emissions with minor changes to production process or added costs

	Clinker	Furnace slag (GGBFS)	Coal combustion residuals (CCR)	Calcined clay (LC3)
Replacement potential	N/A	30-50%[1]	30-35%	30-40%
Availability	3.8 billion Mtpa	520-680 Mtpa	500-800 Mtpa	3.5-5 Mtpa
Availability-adjusted replacement potential	N/A	~10-18%	~10-20%	1-2%
Emissions reduction potential[2]	N/A	~15-30%	~15-30%	~30-40%
Price $/ton	~65-75	~51	~45	~20-35

Abatement cost[3] ($/$tCO_2$e) vs. emission abatement potential (% tCO_2e)



Observations

- Global clinker production is ~3.8 Gt/year. Replacing 50% of global clinker would require SCM supply far above today's ~500 to 600 Mt/year of usable materials; only LC3 offers long-term, scalable supply.
- At the product level, furnace slag has the potential to replace up to 50% of clinker, but global availability limits slag-based substitution.
- Coal combustion residuals (CCR) cements can substitute 30% to 35% at the plant level but globally only ~10% to 20% due to limited supplies of high-quality CCR as coal plants retire.
- LC3 can deliver 30% to 40% clinker reduction, but current industrial capacity is small (~1% to 2% of global cement) and significant new calcination and production infrastructure is required.

[1] 30% to 50% replacement in CEM II/B-S or CEM III/A; up to 60% to 70% in CEM III/B. [2] The % CO_2 reduction achieved if the full technical replacement potential is used. [3] Cost relative to clinker.

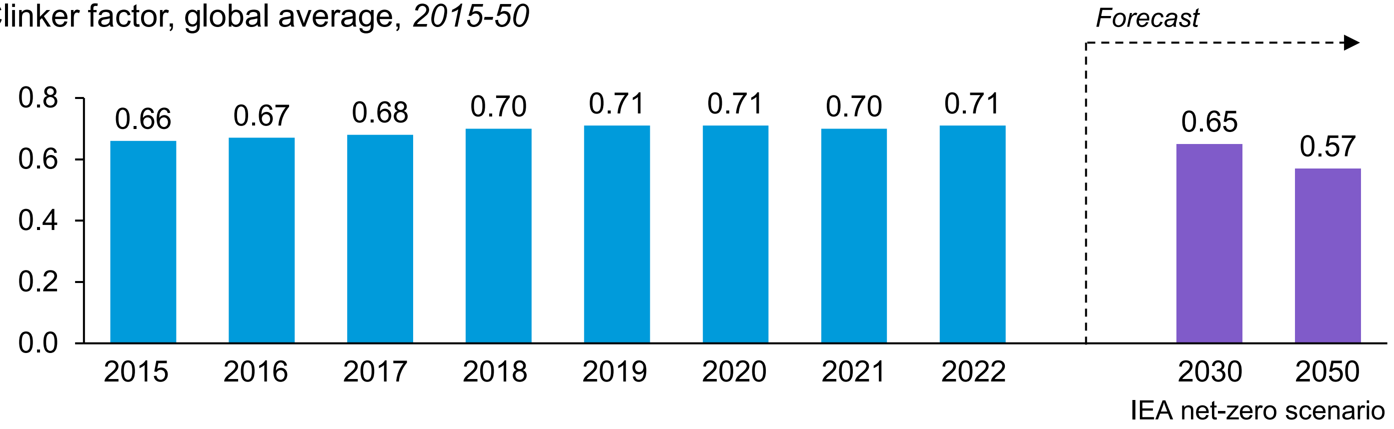
Sources: CKI analysis; DOE, Liftoff Report (2023); RMI, The business case for LC3 (2024); IEA, Net Zero by 2050 (2023); GCCA, Concrete Future Roadmap (2021).

Credit: Nicolas Herrera Isaza, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

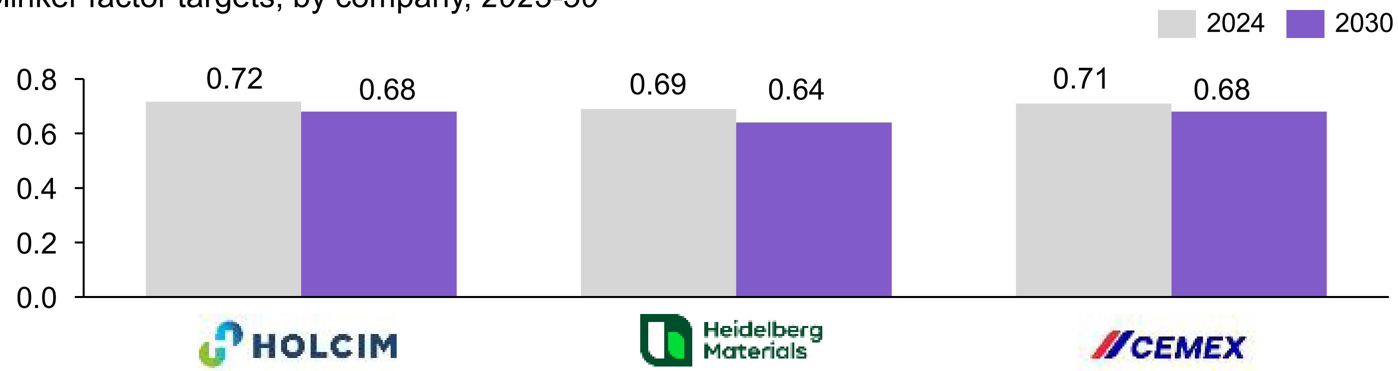
Reducing clinker ratios is a high priority for cement companies, but more support is needed to reach the IEA target of 0.57 by 2050

Clinker factor (clinker-to-cement ratio)

Clinker factor, global average, *2015-50*



Clinker factor targets, by company, *2023-30*



Observations

- Except for Heidelberg, **major cement manufacturers' 2030 targets lag behind the IEA 2030 net-zero scenario.**
- Based on historical trends, reaching IEA's 2030 and 2050 targets will require **more aggressive clinker ratio reductions.**
- This lag may be reflective of certain constraints:
  - **Limited availability of traditional SCMs as by-products decline.** Cement manufacturers have historically relied on by-products such as coal combustion residuals (CCR) and blast furnace slag to reduce the clinker ratios. The phasing out of coal-fired power plants and decarbonization of the steel industry has reduced the ready supply of such by-products.
  - **Scalability issues of new SCMs.** Newer SCMs like calcined clay and natural pozzolans show promise, but scaling up their production presents challenges, as supply chain infrastructure for these alternatives is still relatively immature.
  - **Need for policy support.** Stronger global policy and standardization are required to push the global clinker ratio onto the IEA net-zero trajectory.
  - **Performance trade-offs and market hesitancy around newer blends.** High-blend cements, which use significant amounts of SCMs, can exhibit slow early-age strength development and raise uncertainty about long-term durability. Even if structural integrity is unaffected, it may be challenging to win regulatory and customer approval and acceptance.

Sources: IEA, Cement (2023); Congressional Research Service, Cement (2023); Heidelberg, 2024 Annual Report (2025) and Capital Markets Day (2025); Cemex, 2024 Annual Report (2024); Holcim, 2024 Annual Report (2024); IEA Net Zero by 2050 (2021); RMI, Unleashing the Potential of LC3 (2023); International Cement Review, SCMs: Environmental and Qualitative Benefits (2022).
Credit: Adele Teh, Hoshi Ogawa, Sho Tatsuno, Isabel Hoyos, Jessica Cong, Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

Holcim’s lines of low-carbon cement reduce clinker with SCMs; co-processing plants replace fossil fuels kilns with waste energy

ECOPact The Low-Carbon Concrete

ECOPlanet The Green Cements

30% less carbon emissions compared with OPC

geocycle

~14 million tons of waste recycled in 2023

30% of Holcim’s thermal energy from alternative fuels in 2023

Overview

- ECOPlanet is a portfolio **of low-carbon cement products**; ECOPact includes **ready-mix low-carbon concrete products.**
- Holcim’s **clinker ratio was 0.72** in 2023.
- Company **used 10.2% alternative raw materials** in 2023.

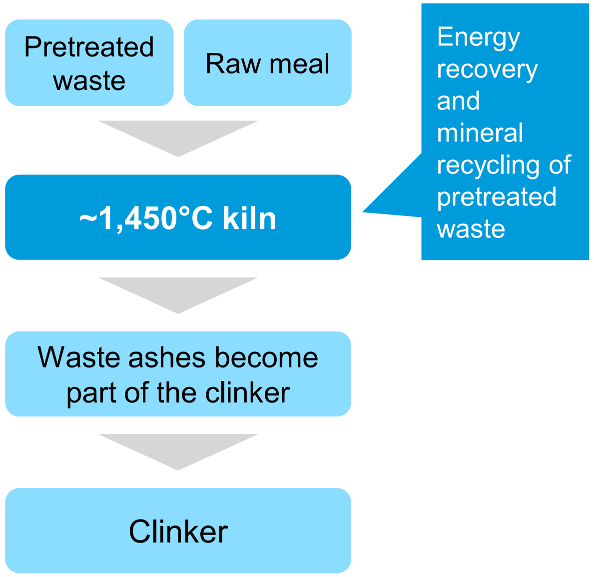
Carbon reduction technologies

- **Alternative raw materials:** Mixing of supplementary cementitious materials and admixtures.
- **Mineral components to reduce clinker factor:** Recycling construction demolition materials; using innovative materials like calcined clay, pozzolans, and reclaimed ashes; and processing industrial waste.
- **Calcined clay to replace limestone-based clinker.**

Co-processing

Co-processing is a **simultaneous waste recycling and energy recovery process** with two primary benefits for cement production:

- **Sustainable waste management:** Co-processing is an **alternative to landfills or traditional incineration**, as it uses unrecyclable waste. By treating waste at high temperatures, the **minerals found in the waste can become part of the clinker.**
- **Fuel alternative for cement kilns:** The **combustion process provides the heat needed** for clinker production and replaces fossil fuel combustion.



Sources: Geocycle, Co-processing (2022); Holcim, Climate report (2023).
Credit: Jessica Cong, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., “Decarbonizing Cement” (16 July 2026).

Eco Material Technologies produces low-carbon ‘pozzolanic cement’ with SCM of proprietary pretreated CCR

Founded: 2022, Utah, U.S.

Announced acquisition by CRH for $2.1 billion (2025)

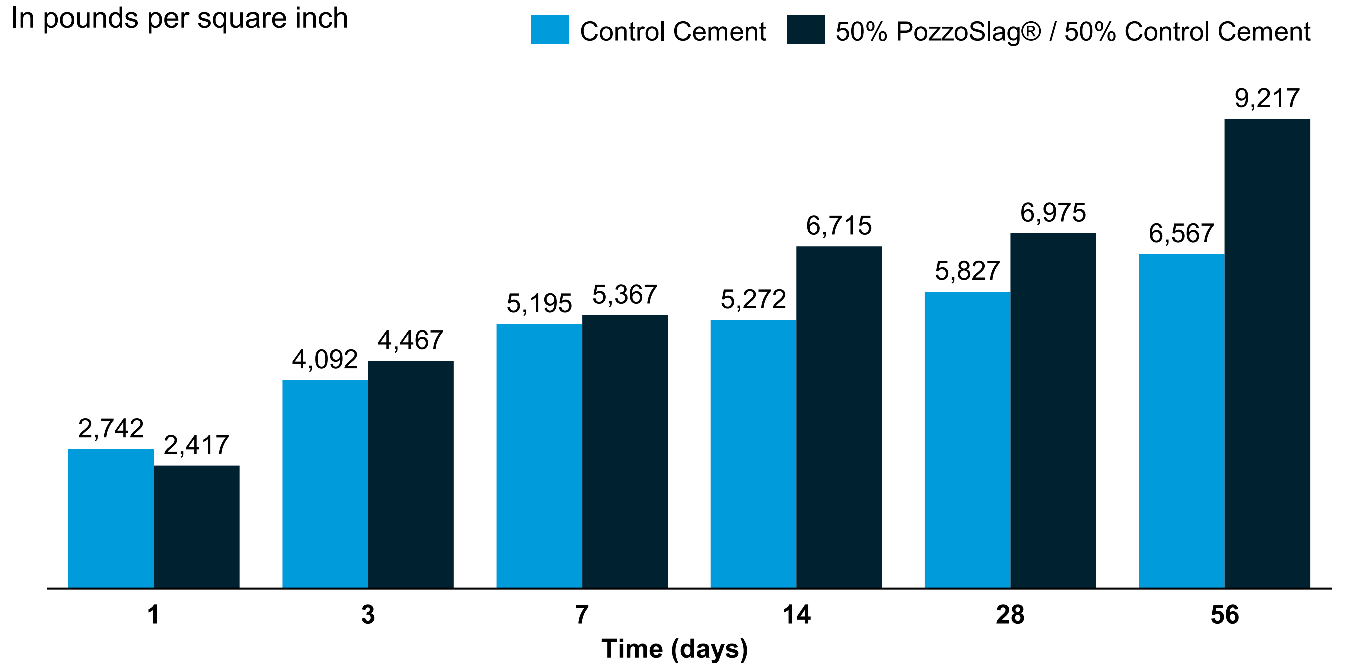
Technology

- Eco Material Technologies uses a **proprietary physical and chemical pretreatment of coal combustion residuals (CCR)** — a common pozzolan — that increases its reactivity.
- PozzoSlag®, the company’s pozzolanic binding product, **can be used as a 50% or higher** ordinary Portland cement replacement and is **priced the same as unalloyed OPC.**
- The newest generation of PozzoSlag® can replace up to 100% of OPC in concrete and **generates up to 99% less CO_2 emissions**.

Challenges

- CCR is a waste product of coal-fueled power plants, which are being retired across the U.S. and globally.
- CCR is produced at coal plants, not where it is needed for construction materials, and its low value makes shipping challenging.

PozzoSlag® can make high-strength, durable concrete



According to testing by Eco Material Technologies, PozzoSlag® is **20% stronger than OPC in 28 days** and continues to gain long-term strength with time.

Sources: Pitchbook, Eco Material Technologies (2025); Eco Material, Green cement (2025); Green Cement, Cement alternatives for a greener future (2025); Forbes, Eco Material’s cement is transforming construction (2023); CRH, CRH to Acquire Eco Material Technologies (2025).
Credit: Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., “Decarbonizing Cement” (16 July 2026).

CalPortland is licensing Solidia's patent, using carbonation to produce cement that stores CO_2

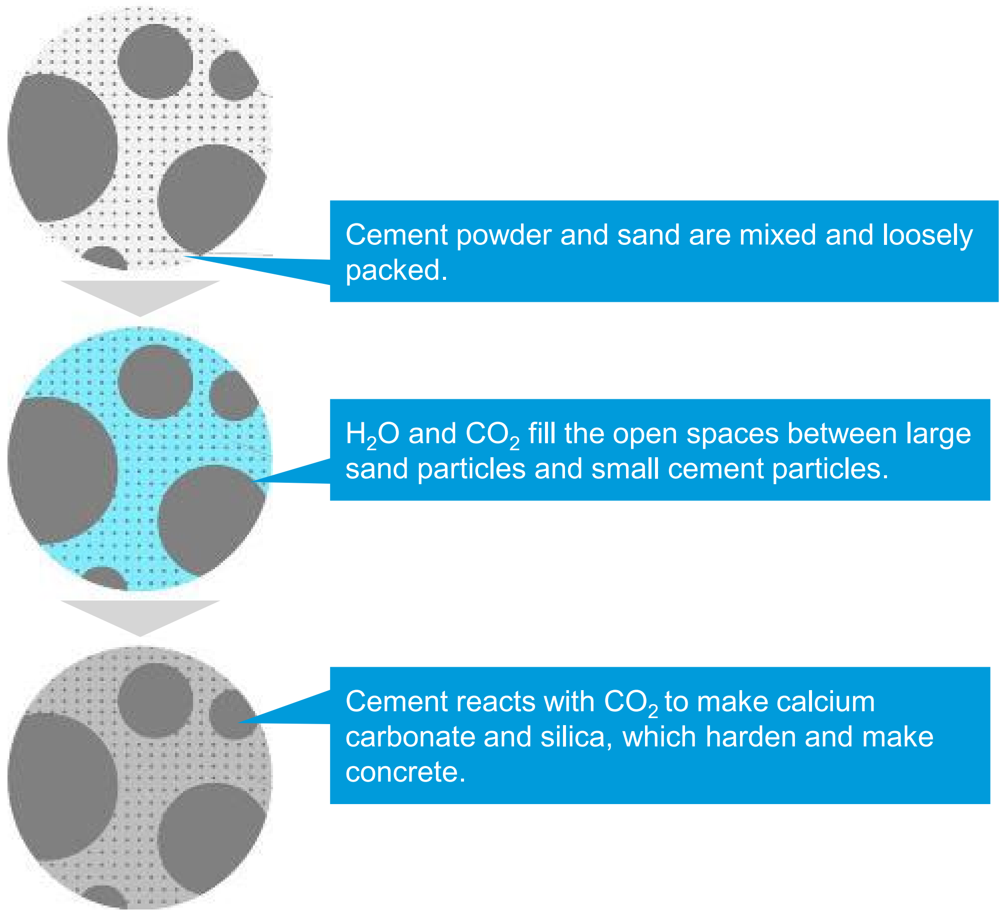
Licensing agreement: June 2024

Licensing agreement

- CalPortland entered a **patent licensing agreement with Solidia** that grants the company limited rights to use its technology and purchase some of its laboratory and plant assets.

Technology

- Produces cement with up to 30% less carbon emissions and concrete with up to 50% less emissions.
- Uses the same raw materials and equipment as ordinary Portland cement, with a lower proportion of limestone and at lower production temperatures.
- The cement gains strength through **carbonation — exposure to CO_2 — rather than through hydration, as with OPC.** It transforms gaseous CO_2, which may come from industrial emissions, into solid carbonates. This process allows the cement to **both utilize and store CO_2.**



Sources: CalPortland, Solidia licenses low carbon cement (2024); Solidia (2024).
Credit: Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

Prometheus Materials leverages algae's natural biomineralization to create a net-zero emissions cement replacement

Founded: 2021, Colorado, U.S.

Total funding raised to date: $14.3 million

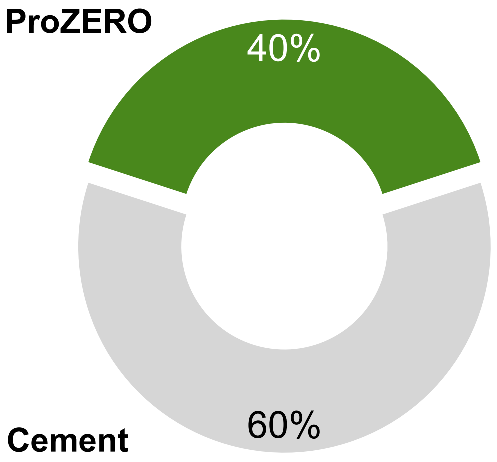
Technology

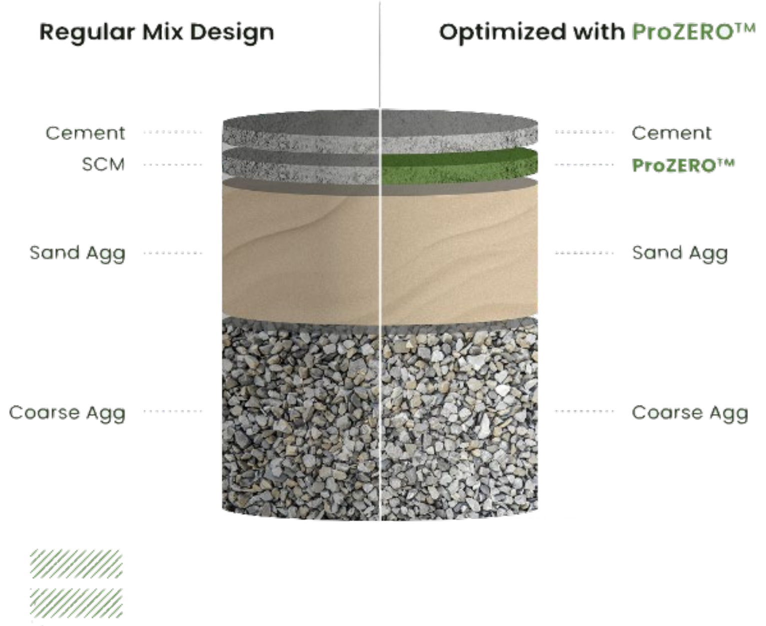
- Prometheus creates ProZERO® by growing **microalgae** in large ponds, which **naturally biomineralizes and creates limestone organically.** After drying, it is treated with a proprietary binder and is then ready to be supplemented into any cement mix.
- The natural cycle of **microalgae sequesters carbon** and **avoids** the need for **mining and kilns.**
- A mix that blends traditional cement with **~40% of ProZERO can achieve carbon negativity.**

Current achievements

- Products made using ProZERO's Ready Mix supplemental blend **comply with industry standards** for load-bearing and non-load-bearing blocks. Other ProZERO products include Flowable Fill and Manufactured Goods (blocks, pavers, etc.).
- Prometheus' products are estimated to have achieved carbon neutrality in a case study project for a building's exterior facade in Boulder, CO.
- The company signed a landmark agreement to provide ProZERO cement for the construction of New York Climate Exchange's Campus.

Example: Mix Optimized with ProZERO





104%

Reduction in global warming potential (GWP)

Sources: CB Insights, Prometheus Materials (2025); Prometheus Materials (2025); Yahoo Finance, Prometheus Completes Landmark Collaboration (2025).
Credit: Ariela Farchi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

Thermal batteries can deliver extreme high temperatures powered by electricity, tackling thermal emissions

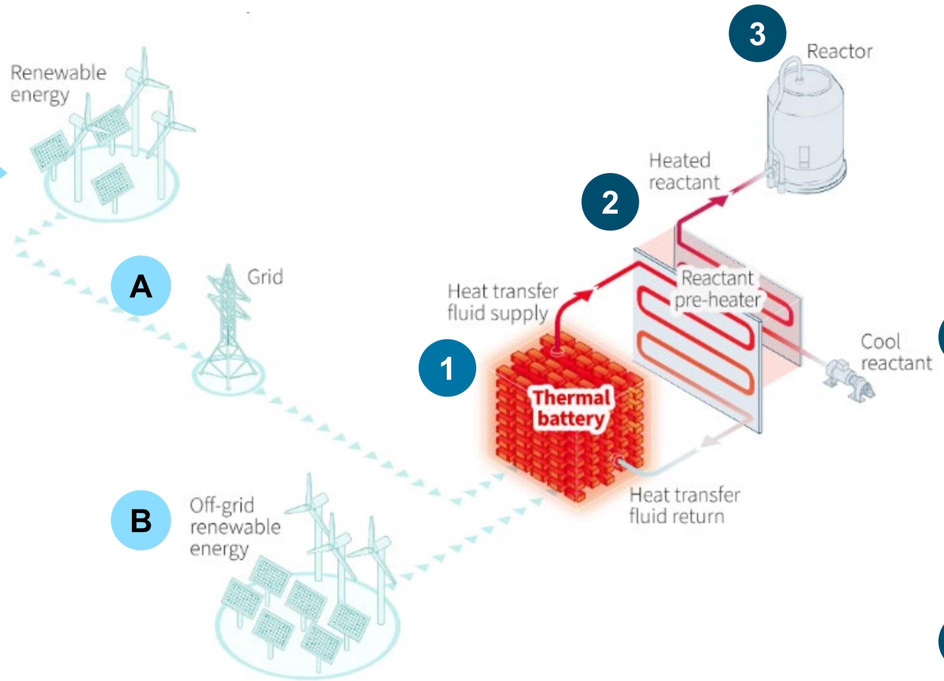
Electricity sourcing → **Heat generation and storage** → **Heat delivery**

A Grid power

- Power is bought at market prices (wholesale market or long-term contracts).
- Electricity may be from renewables or fossil sources (e.g., natural gas). To achieve decarbonization, it is key to look for cleaner grids.
- Prices must be considered, ideally seeking cost-competitive renewable energy deals.

B Off-grid power

- Can be standalone or work in parallel to grid power.
- Guarantees greater share of clean energy.
- Requires greater capital investment.
- Electricity cost may be lower than buying from the grid.



1

- Electric heaters are embedded in a specific medium (e.g., thermal bricks) and heat up to the targeted temperature.
- Temperatures can reach up to 1,500°C with current technology.
- Thermal radiation can be stored for hours or days. **Thermal insulation is key.**

2

- Air flows through the battery, spreading the stored heat.
- Delivery rate can be adjusted by managing air flow.
- Air can also be transformed into steam, depending on the industrial needs.

3

- Hot air or steam can then be delivered steadily at desired temperatures and rates.

Sources: RMI, Thermal Batteries (2024); CKI analysis.
Credit: Nicolas Herrera Isaza, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

Three companies leading thermal battery industry within cement kiln temperature range are at early commercialization stage

Founding year

	Headquarters	Thermal battery model	Temperature range	Storage medium	Commercialization status	Funding and target geographies	Investors
2017 ANTORA	**U.S.**	Heatcore (HC) and Heatmax (HM)	< 400°C (HC) < 1,500°C (HM)	Carbon blocks	Early commercialization	**VC: $200M**; Grant: $4M U.S., Europe	Breakthrough Energy, NextEra Energy, BHP Ventures, arpa-e, Lowercarbon Capital, Decarbonization Partners (BlackRock, Temasek), Shell Ventures
2020 RONDO	**U.S.**	RHB300	< 1,500°C	Bricks	Early commercialization	**VC: $82M** U.S., Middle East, Asia	Breakthrough Energy, Titan Cement Group, Microsoft, RioTinto, Energy Impact Partners
2014 KRAFTBLOCK	**Germany**	Net-Zero Heat System	< 1,300°C	Not disclosed	Early commercialization	**VC: $22M;** Grant: $2M EU, U.S.	Shell Ventures, a&g, TechEnergy Ventures, future energy ventures, Redstone, Moore Strategic Ventures
2021 ELECTRIFIED THERMAL SOLUTIONS	**U.S.**	Joule Hive Thermal Battery	< 1,800°C	Firebricks	Pilot	**VC + Debt: $44M**; Grant: $5M U.S.	U.S. Department of Energy, Clean Energy Ventures, Vale, EDP Ventures, Holcim Maqer, Cemex Ventures, Starlight Ventures
2012 BRENMILLER THERMAL ENERGY STORAGE	**Israel → U.S.**	bGen ZERO	130-750°C Not at cement kiln temperatures yet	Crushed rocks	Commercialization	**$3.3M valuation**, 2022 IPO	Alpha Capital Anstalt, J.P.Morgan, UBS, citi

Sources: CB Insights, Thermal energy storage developers (2025); Antora (2025); Rondo Energy (2025); Kraftblock (2025); Electrified Thermal Solutions (2025).
Credit: Nicolas Herrera Isaza, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

Brimstone eliminates chemical emissions from traditional cement production by replacing limestone with calcium silicate rocks

BRIMSTONE

Founded: 2019, California, U.S.

Total funding raised to date: $72 million

Technology

- Brimstone makes cement from **carbon-free calcium silicate rocks**, eliminating the calcination process, which accounts for 60% of CO_2 emissions in traditional cement production.
- Brimstone's process creates three key co-products: **ASTM C150 Portland cement, SCMs, and smelter-grade alumina.**
- **At an industrial scale** of production, all three co-products could be **sold at competitive market prices.**

Current achievements

- Advanced in the construction of **a commercial-scale plant to produce 140,000 metric tons per year** of decarbonized industry-standard ASTM C150 Portland cement, SCMs, and alumina.
- Received **third-party certification that its cement meets or exceeds ASTM C150** standards for OPC.
- Signed a **commercial agreement with Amazon, which will reserve annual volumes of Brimstone's OPC and SCMs**, pending successful completion of testing and commercialization to scale up requirements.

CALCIUM-BEARING SILICATE ROCK

PORTLAND CEMENT

SUPPLEMENTARY CEMENTITIOUS MATERIALS (SCMs)

SMELTER-GRADE ALUMINA

Sources: Brimstone (2024); Advanced Research Projects Agency-Energy (ARPA-E) (2024); DOE, Awarded projects: cement and concrete (2024); CB Insights, Brimstone Energy (2025); Business Wire, Amazon and Brimstone collaboration (2025).

Credit: Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Ariela Farchi, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

Sublime replaces high-heat kilns with electrochemistry and limestone with alternative feedstocks to reduce ~90% emissions

Sublime Systems

Founded: 2020, Massachusetts, U.S.

Total funding raised to date: $53 million

Technology

- Sublime's technology uses an **electrochemical process that replaces carbon-intensive limestone with abundant non-carbonate feedstocks** like calcium silicate minerals or industrial waste.
- **Sublime uses electricity, rather than heat**, to break down feedstocks and produce a calcium silica cement, to displace ordinary Portland cement (OPC).
- Provides a product that **complies with ASTM C1157 standards.**

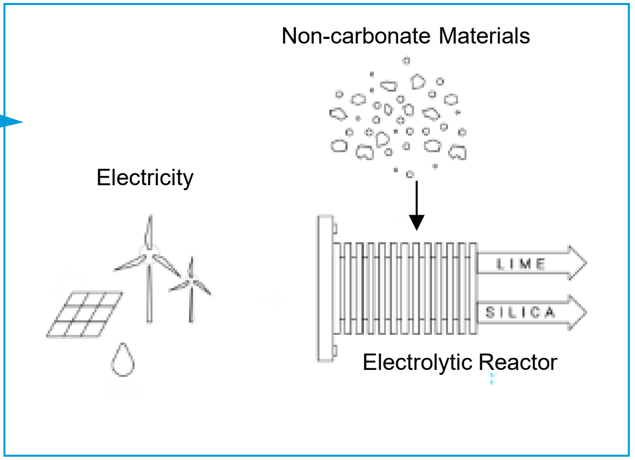
Current achievements

- **Sublime was planning to build a new, ultralow carbon cement manufacturing facility** in Holyoke, Massachusetts — Sublime's first commercial manufacturing scale-up. However**, it paused the plant development in December 2025 after losing a federal grant.**
- It received an **LCA study validating that its cement manufacturing process can reduce 90% of GHG emissions.** Sublime's cement has a GWP[1] of 72 $kgCO_2$/t of cement, while OPC is 922 $kgCO_2$/ton.
- The company signed an **agreement with Microsoft for 623K tons over a six- to nine-year** period.

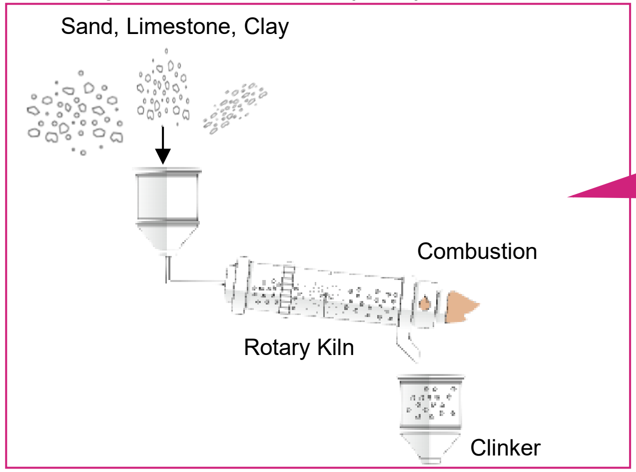
Electricity + non-carbonate minerals = CO_2 avoided

Potential emission sources: Electricity grid mix

Sublime Systems Process



Ordinary Portland Cement (OPC) Process



Key emission sources: Limestone, combustion
Coal + limestone = CO_2
1 ton OPC = ~1 ton CO_2

[1] GWP: global warming potential.

Sources: Sublime (2025); Advanced Research Projects Agency-Energy (ARPA-E) (2024); DOE, Awarded projects: Cement and concrete (2024); CB Insights, Sublime Systems (2025); Bloomberg News, Microsoft deal for green cements (2025); S&P Global, Sublime pauses Holyoke Plant (2025).

Credit: Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

Furno’s modular, electrified reactors improve efficiency, reduce limestone use, and produce a high-purity CO_2 for easier capture

Founded: 2020, California, U.S.

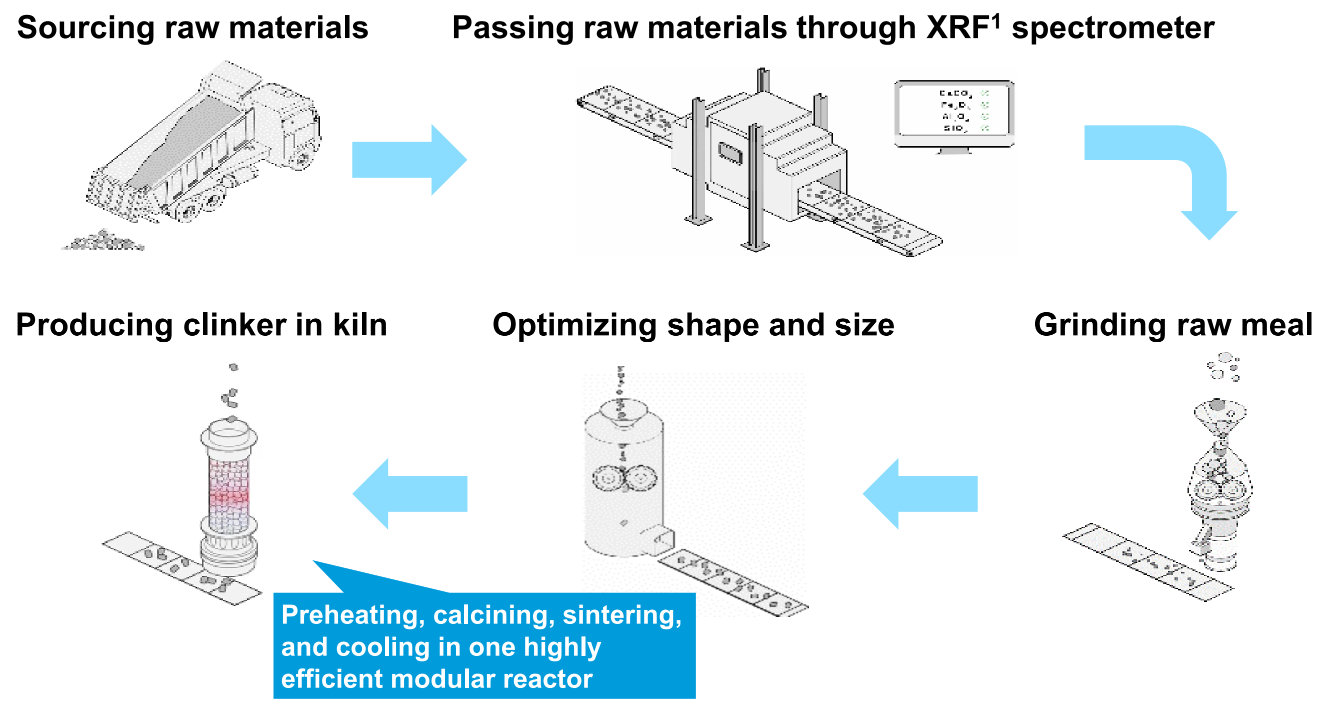
Total funding raised to date: $12.4 million

Technology

- **Modular, high-efficiency mini-kiln:** Continuous-flow reactor replaces rotary kilns, with **~80% thermal efficiency and precise temperature control.**
- **Lower-carbon process design:** Operates with **gas/renewable**; uses **alternative calcium-rich by-products to cut limestone-related CO_2** and **produces a high-purity CO_2 stream suitable for CCUS.**

Current achievements

- Funding and deployment: **Raised $6.5M** seed round and secured a **$20M DOE grant** to build its first commercial pilot plant.
- Product certification: Achieved **ASTM C150 cement certification**, with independent tests showing ~2x required strength.
- Emissions reductions demonstrated: Pilot design shows **~70% fuel-emissions reduction potential and substantial limestone-replacement capability.**



Key strategies

- Replace the rotary kiln with **modular, electrified reactors to improve efficiency and lower CapEx.**
- Enable **decentralized, scalable cement** production to **reduce transport costs and allow rapid, incremental deployment.**
- Produce a **high-purity CO_2 stream to support low-cost carbon capture.**

[1] XRF: X-ray fluorescence is a non-destructive analytical technique that determines the elemental composition of a sample.

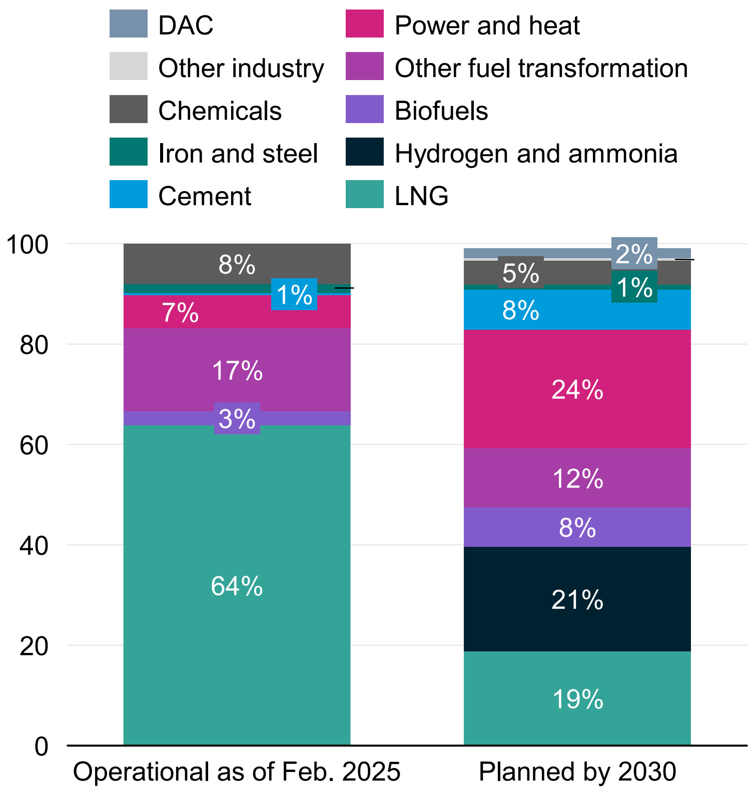
Sources: Pitchbook, Furno (2025); Furno (2024); Business Wire, Furno secures seed funding (2024); TechCrunch, Furno’s super-efficient modular kilns (2024); Cement Products, Furno cement plant concept (2024); Global Cement, Furno Materials ‘low carbon’ cement plant in Chicago (2024).

Credit: Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., “Decarbonizing Cement” (16 July 2026).

Carbon capture, utilization, and storage is expected to abate remaining emissions in the cement industry’s path to net zero

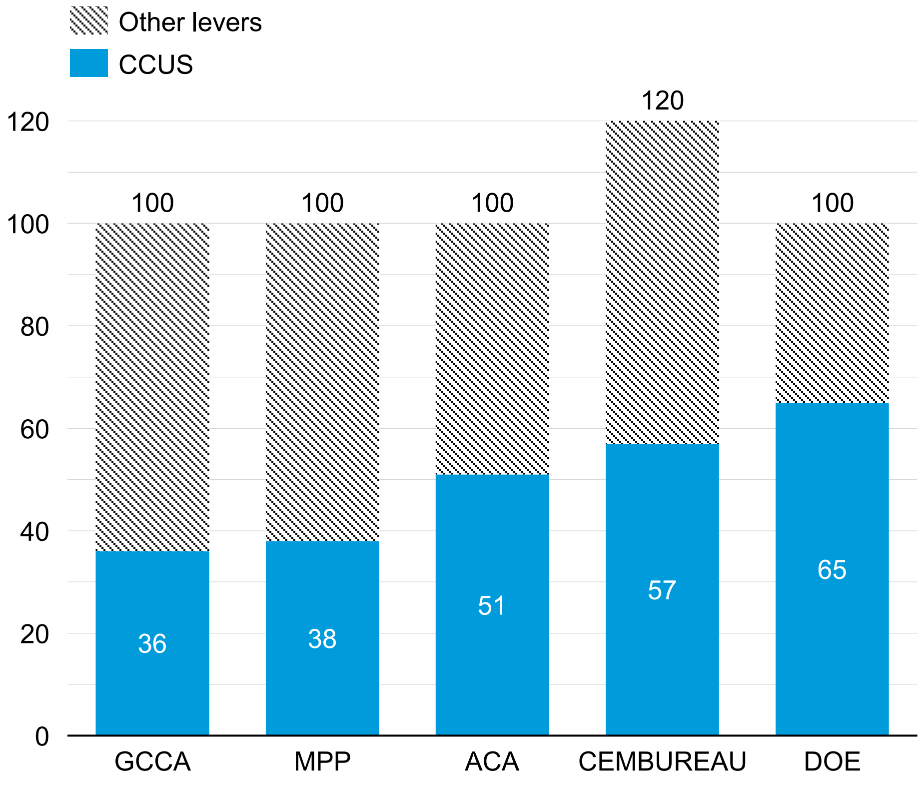
CCUS capacity for cement is expected to grow ~9x by 2030

Operational and planned CCUS capacity by industry, *%*



Across scenarios, CCUS is expected to abate 35% to 65% of cement emissions

Cement abatement from CCUS by roadmap, *2050, %*



Observations

- As the energy industry continues to phase out fossil fuels, CCUS will play **a bigger role in decarbonizing hard-to-abate industries** like cement and steel, as opposed to oil and gas.
- As of Q1 2025, **global CO_2 capture and storage capacity in operation reached over 50 Mt.** By 2030, capture capacity is expected to reach **430 Mt** based on the current project pipeline, with storage capacity at 670 Mt.
- **Current cement CCUS plants:**
  - **Brevik CCS, Norway (Heidelberg):** First industrial-scale **CCS cement plant**, designed to capture up to **400K tons of CO_2 annually.** As of May 2025, the plant captured and stored its first 1K tons of CO_2.
  - **Lengfurt Cap2U, Germany (Heidelberg and Linde):** First industrial-scale **CCU cement plant**, designed to capture up to 70K tons of **CO_2 annually.**

Sources: IEA, Net Zero by 2050 (2021); IEA, CCUS Projects Explorer (2025); IEA, Demand and Supply Measures for the Steel and Cement Transition (2025); International Cement Review, China CCUS focus (2024); ICR, China Starts CCUS Focus (2023); Heidelberg, Brevik CCS (2025); GCCA, Concrete Future (2021); MPP, Making Net-Zero Concrete and Cement Possible (2023); PCA, Roadmap to Carbon Neutrality (2024); DOE, Industrial Decarbonization Roadmap (2022); CEMBUREAU, From Ambition to Deployment (2024).

Credit: Adele Teh, Hoshi Ogawa, Sho Tatsuno, Isabel Hoyos, Jessica Cong, Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., “Decarbonizing Cement” (16 July 2026).

Oxy-combustion enables high-purity CO_2 capture and reshapes CCUS economics for cement

Oxy-combustion boosts flue gas CO_2 concentration from ~15% to >80%, reducing energy required for capture and enabling >95% capture rates with >99.9% purity

1 Produce pure oxygen

An on-site **air separation unit (ASU)** takes in ambient air and cryogenically separates it, producing high-purity oxygen.

2 Produce flue gas via oxy-combustion

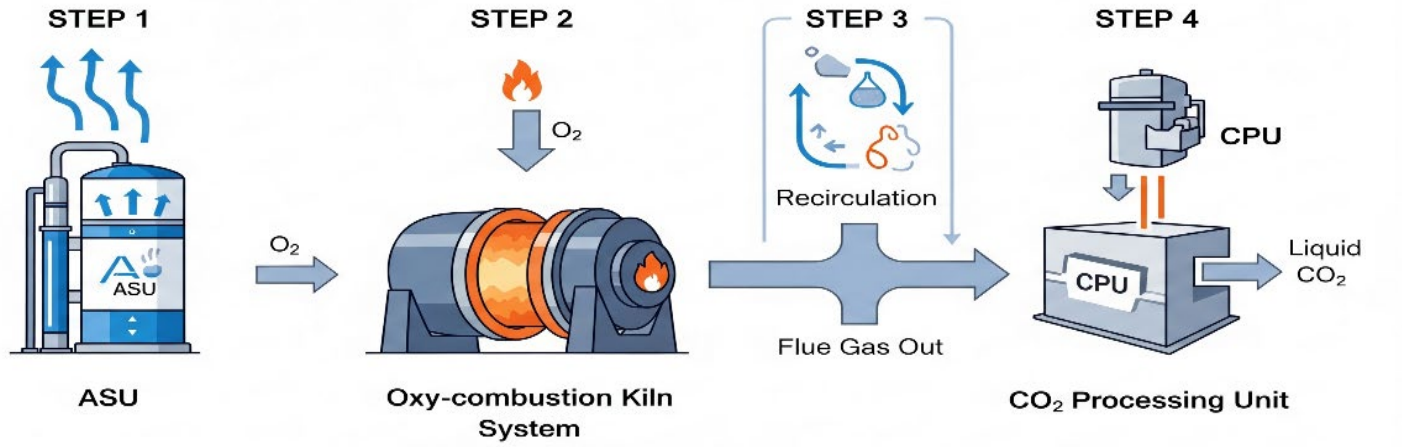
Fuel is burned using pure oxygen and CO_2 gas to create an **80% to 95% concentrated CO_2 exhaust stream.**

3 Split and recirculate flue gas

For the **recirculation loop**, a large portion is cooled and piped back. For the capture stream, the remaining gas is directed away for final processing.

4 Purify the final CO_2 product

The captured CO_2 stream is sent to a CO_2 **processing unit (CPU).** A final product of **>99.9%** pure liquid CO_2 is ready for transport, utilization, or storage.



Observations

- Purity and concentration improvements mean **captured CO_2 can be converted into salable products** (e.g., synthetic fuels, building materials), shifting CCUS from a compliance cost to a potential value-generating asset.
- The technology can integrate into existing kilns with **minimal redesign, enabling rapid, policy-driven deployment** and making it especially attractive in markets pursuing **state-led decarbonization strategies.**
- By cutting capture costs **by 30% to 50% and pairing well with low-carbon or hydrogen fuels**, oxy-fuel CCUS transforms cement capture economics and offers a scalable pathway toward near-zero emissions.

Sources: Sina Finance, Sinoma (2025); Sinoma, News (2025); Sinoma, TCDR (2024).
Credit: Anda Wang, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

CCUS is complementary to near-term solutions but is not a replacement for long-term decarbonization technologies

	Decarbonization levers	Relevance to CCUS/CCS	Explanation
Near term	Energy efficiency	Complementary	Efficiency lowers emissions baseline, reducing capture volume and cost per ton.
Near term	Alternative fuels	Complementary	Fuel switch cuts thermal emissions; CCS can capture remaining process CO_2.
Near term	Blended cements (SCMs/LC3)	Complementary	Blended cements reduce clinker demand and chemical emissions; CCS targets residual emissions.
Long term	Thermal batteries	Partially substitutable	Electrification cuts combustion emissions; CCS is still useful for process emissions.
Long term	Alternative feedstocks	Partially substitutable	If feedstock avoids process CO_2, CCS becomes less necessary — but may still capture other emissions.
Long term	Electrochemical production	Largely substitutable	Low-heat, non-carbonate process eliminates need for CCS altogether; there is competition for mineral feedstocks (e.g., calcium, magnesium).

Observations

- CCUS/CCS is a **transitional solution** that cuts emissions from existing plants and complements other measures, but its role diminishes as other production methods mature.
- **Opportunities:**
  - Decarbonize existing cement plants **through retrofitting** vs. requiring a full rebuild.
  - **Capture up to ~61%[1] of emissions**, including unavoidable process CO_2 from calcination.
  - Reduce costs across multiple sectors by sharing CO_2 pipelines and storage hubs.
- **Challenges:**
  - **Has high CapEx and OpEx cost** due to the need for capture units, transport pipelines, and storage infrastructure ($60-$190/t CO_2).
  - Requires nearby geological storage or CO_2 utilization opportunities.
  - Depends on regional networks and regulatory support.

[1] ~60% reflects the approximate emissions gap after other measures, not a fixed technical limit. Realized potential depends on retrofit rates, capture efficiency, and integration with utilization pathways.

Sources: DOE, Liftoff Report (2023); Mission Possible, Making Net-Zero Concrete and Cement Possible (2023); CATF, Recasting the Future (2025); ACM, Roadmap to Carbon Neutrality (2021); GCCA, Concrete Future (2022); ClimateWorks Foundation, Low-carbon cement (2023); Energies, Alternative Fuels and Energy Efficiency in Cement (2023); International Journal of Greenhouse Gas Control, BioCCS in cement (2023); IEA, Bioenergy Annual Report (2022); RMI, The business case for LC3 (2024); Energy Innovation, Industrial Thermal Batteries (2023).

Credit: Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

Sinoma's accelerated innovation in China shows that policy-backed R&D can enable technologies like CCUS to scale at speed

CNBM | sinoma

Founded: 1983, Beijing, China

Market cap $5.2 billion

Decarbonization strategy

1. **Energy efficiency:** The Huaikan South production line project helped **save 54M kWh/year and reduce CO_2 emissions by 160,000 tons/year.**
2. **Alternative fuels:** The SPL clay calcination EPC project in France can **reduce CO2 by 100,000 tons/year** with the **alternative fuel rate reaching 100%.**
3. **Low-carbon cement:** High belite cement tech applied in the Jianwen project in Zhengzhou used **proprietary tech to substitute clinker with other materials.**
4. **CCUS: The world's largest** industrial application of oxyfuel tech in Qingzhou used **proprietary oxy-combustion tech to capture CO_2.**

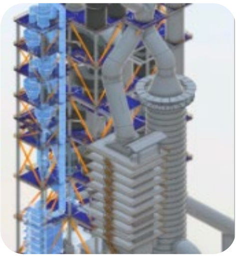
Observations

- **State-led mandates, financing, and permitting** compressed projected delivery timelines from years to months.
- Sinoma's **co-development of capture, power supply, and CO2 utilization** improves project economics and reduced risk.
- Oxy-fuel combustion was viable at this scale through **national decarbonization targets and industrial policy support.**
- Sinoma's case demonstrates how state-owned enterprises can **mobilize capital, coordinate infrastructure, and scale CCUS** in the cement sector.

Qingzhou is the world's first and largest cement oxy-fuel CC project

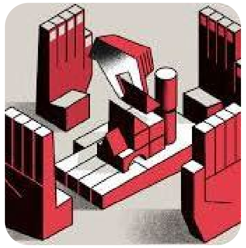
Project highlights

- **Massive scale:** Captures 200,000 tons of CO_2 per year
- **Rapid development:** Design completed Dec. 2022 → construction completed Dec. 2023 → commissioned Jan. 2024



Project impacts

- **Resource utilization:** Captured CO_2 is used for various industrial purposes, including enhanced oil recovery.
- **Industry milestone:** Represents a significant step forward in making carbon capture more economically viable for the cement industry.



Industrial policy

- **Policy mandate:** National "dual carbon" goals provide the strategic certainty for state-owned enterprises to make massive investments.
- **State-led execution:** The state-led model enables rapid resource mobilization and complex cross-sector integration, dramatically accelerating project timelines.

Sources: Sina Finance, Sinoma (2025); Sinoma, News (2025); Sinoma, TCDR (2024); Sinoma International, Sinoma International Empowering High-Quality Development of Cement Industry - Solutions for Green & Intelligent System (2024).
Credit: Anda Wang, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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Fortera's ReCarb technology uses mineral recarbonation to produce SCMs from captured carbon

fortera

Founded: 2019, California, U.S.

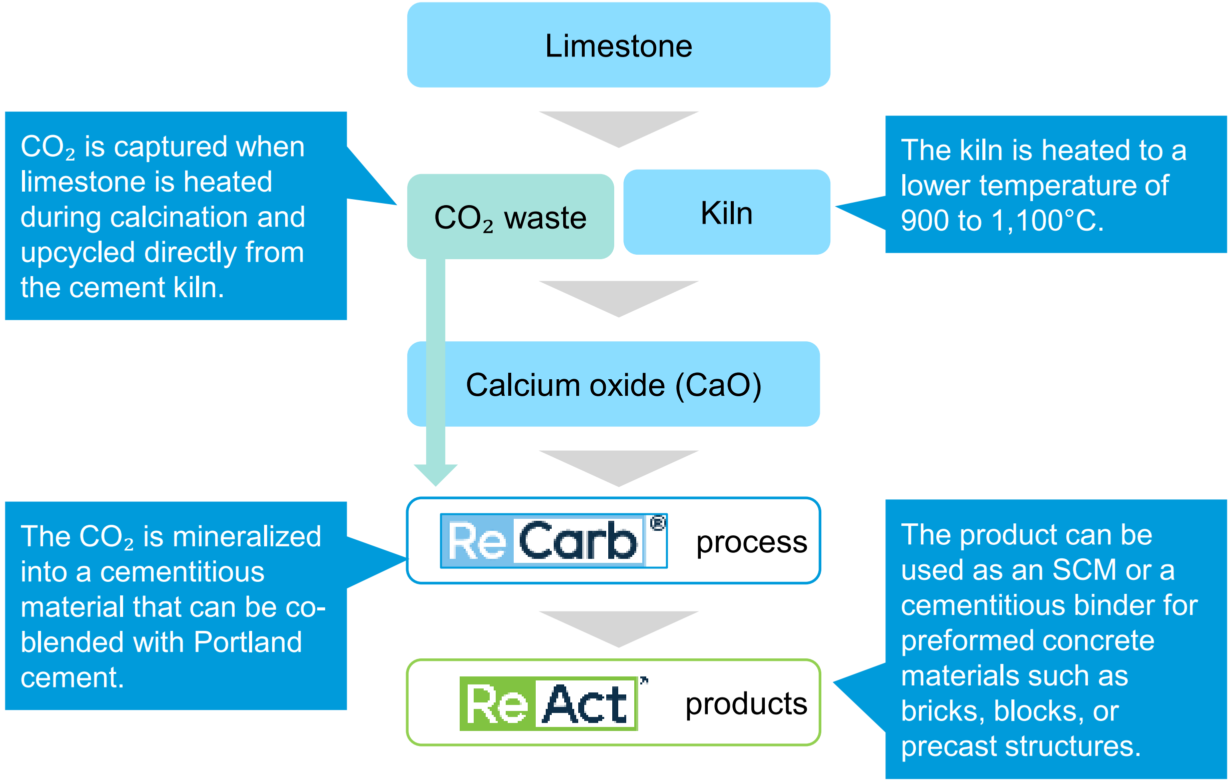
Total funding raised to date: $119 million

Technology

- Fortera's **ReCarb** process is a bolt-on solution that captures CO_2 released during clinker production and **mineralizes it into carbonate-based cementitious material**, which can serve as a supplementary cementitious material (SCM) or binder for precast products.
- It forms stable **calcium carbonate phases (e.g., vaterite and others)**, effectively locking in CO_2 while reducing calcination emissions.

Current achievements

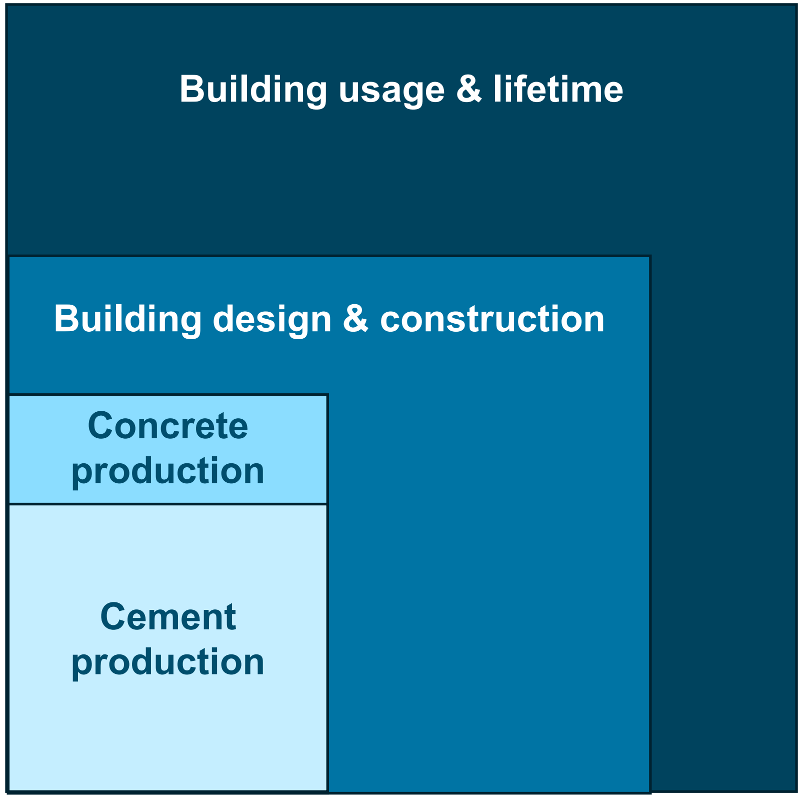
- In April 2024, Fortera opened its **first industrial green cement plant** adjacent to CalPortland's Redding, CA, facility, aiming to produce **~15,000 tons** of **ReAct** low-carbon cement per year and **capture ~6,600 tons of CO_2.**



Sources: Pitchbook, Fortera (2025); Fortera Global, ReCarb plants (2024); Global Cement, Low-CO2 inspired by nature (2021); Business Wire, Fortera opens first industrial green cement plant (2024).
Credit: Jessica Cong, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

Demand-side solutions offer significant additional opportunities for concrete emissions reductions across the value chain

Opportunities to cut material demand and carbon emissions exist across the entire building lifecycle



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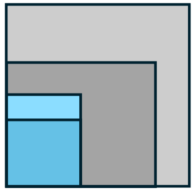
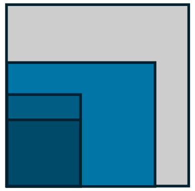


Efficiency in concrete production

- Shift from small-site batching to industrialized processes ensures better mix control.
- Use of admixtures improves aggregate processing.
    - Already applied in some countries.
- **Abatement potential: ~400 MtCO_2 per year by 2050.**

2



Efficiency in design and construction

- Material-efficient design, such as slab geometry, column spacing, and optimized strength, is reducing concrete demand.
- Smart design systems reduce concrete demand.
- Requires emissions to be a design parameter.
- **Abatement potential: ~800 MtCO_2 per year by 2050.**

3

Recarbonization

- Natural CO_2 uptake by concrete during lifetime.
- 12% to 23% of process emissions can be reabsorbed.
- Requires access to demolition waste for maximum effect.
- **Abatement potential: ~250 MtCO_2 per year by 2050.**

Smart design systems, such as 3D printing in concrete, can reduce material use by up to 50%

3D printing innovations in concrete and construction

Taller wind turbines through 3D-printed concrete bases:

Holcim, GE Renewable Energy, and COBOD are collaborating to develop **3D-printed concrete bases for wind turbines up to 200 meters.**

Traditionally bases — made from steel or precast concrete — are typically capped at ~100 meters, limited by the 4.5-meter transport diameter that makes larger bases uneconomical.

Scaling affordable housing in Africa:

14Trees, a joint venture between Holcim and British International Investment, launched **Africa's largest 3D-printed affordable housing project** in Kilifi, Kenya, in 2021.

By 2023, the first 10 homes in the 52-unit complex were completed.

Enabling conventional concrete in 3D printing:

In 2022, Cemex and COBOD introduced **D.fab, a proprietary admixture that allows 3D printing with standard ready-mix concrete**.

The innovation reduces costs and material waste, making digital construction more accessible and commercially viable.

Use cases

- 3D printing has been used to develop innovative and sustainable solutions in emerging markets for:
  - Modular solutions for low-cost housing.
  - Resource-efficient buildings and schools.
  - Concrete bases for wind turbines.
- 3D printing can reduce material use by up to 50% and reduce the time and cost for infrastructure projects.

Source: Holcim (2020).
Credit: Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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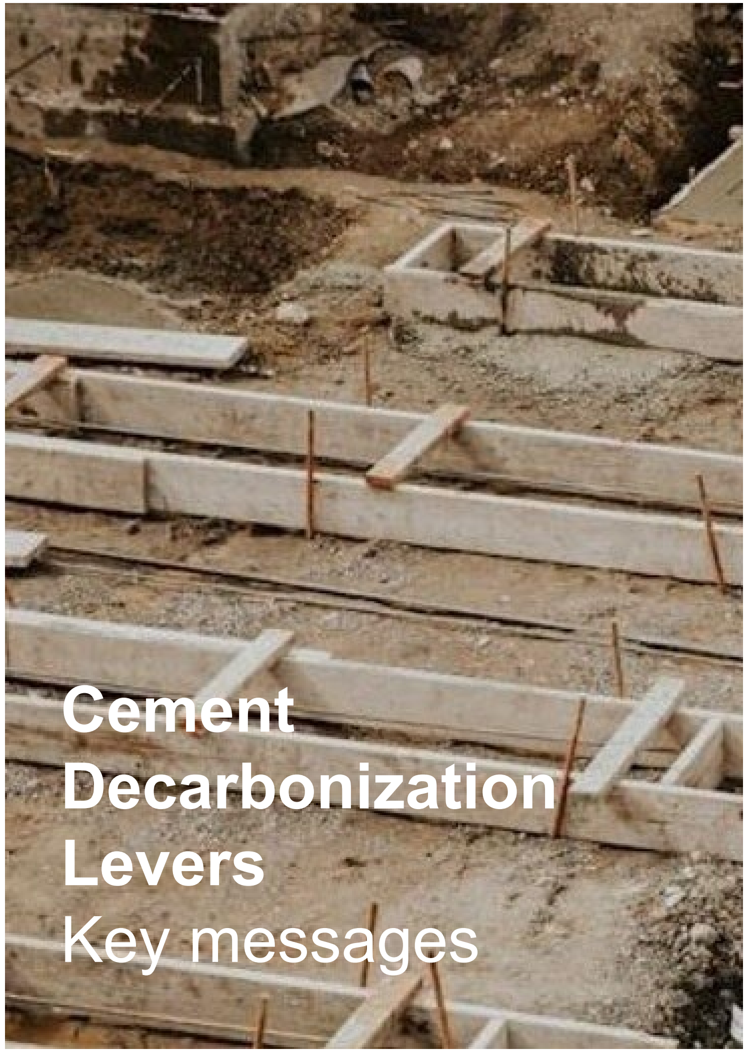
Cement Decarbonization Levers



Decarbonizing cement requires coordinated action across **technology, finance, and policy.** While solutions are emerging — from CCUS in the Global North to LC3 in the Global South — adoption remains uneven due to structural and financial barriers.

- Most low-carbon levers remain **pre-commercial**, with limited real-world validation.
- **Long certification cycles and strict durability standards** slow uptake of new materials and blends.
- **Knowledge sharing is limited**, as proprietary technologies dominate the early innovation landscape.

Capital intensity and limited finance constrain scale-up.

- New cement plants require high CapEx at commercial scale; project finance options are scarce.
- The **EU's Innovation Fund has directed over €2.4 billion** to cement and lime projects — primarily CCUS — but access is concentrated in Europe.
- Achieving a net-zero trajectory will require a **35% increase in investment by 2050, including $440 billion in enabling infrastructure** (CCUS, SCM, and energy systems).

Fragmented value chains slow demand creation.

- 70% to 75% of cement used ready-mix concrete with short procurement cycles.
- Government procurement (~50% of U.S. demand) is emerging as a key early market.
- Lack of unified standards and carbon accounting hinders product comparison.

Policy strength and technology pathways diverge by region.

- EU: Strongest mix (**ETS, CBAM, Innovation Fund**), but rising carbon costs challenge competitiveness.
- U.S.: Incentive-driven (**IRA 45Q, IDP, Buy Clean**) yet fragmented across states.
- Asia Pacific: Largest producer but **under-regulated; LC3 and SCMs are favored** as lower-cost decarbonization paths.

Cement and concrete companies must work in tandem to decarbonize the construction value chain

Key roles for cement industry decarbonization across the value chain

Cement producers	Concrete producers	Concrete suppliers	Construction	End users
• **Implement** emissions-reduction technologies like **CCUS, alternative fuels, and kiln electrification.** • **Replace** clinker with **SCMs** (e.g., **CCR**, **calcined clay**). • **Improve thermal** and **electrical efficiency.**	• **Reduce** embodied carbon by lowering **clinker factor** in mixes. • **Use alternative binders** and **carbon-cured concrete.** • **Shift** to **renewable energy sources.**	• **Ensure** wide availability of **low-carbon concrete mixes.** • **Reduce** emissions in **transport** and **batching operations.** • **Lower** building **carbon footprint** by optimizing **design** to **codes and standards.** • **Improve job site efficiency**. **Cut waste** — 5% of concrete is returned **unused.**	• **Specify requests for low-carbon materials** in **tenders.** • **Reduce waste** and **optimize structural design.** • **Drive material efficiency** across the **project lifecycle.**	• **Boost** demand for **low-carbon cement** and **concrete,** specifically by **public sector** and governments. • **Shape design** and **material choices** upstream. • **Build markets** via **long-term commitments** and **investments.** • **Use policy** and **finance tools** to enable **innovation** and **decarbonization.**

Observations

- **~70% to 75% of cement** goes into **ready-mix concrete**, prepared for roads, buildings, and other uses. This segment has strict standards and is **hard to break into**.
- **~10% to 15% of cement is used in precast concrete**, which is mixed, molded, and cured before reaching the construction site. This segment can be **more open to new players.**
- In the U.S., **government procurement accounts for ~50% of concrete demand**, giving public sector spending a significant role in market-side decarbonization and in **driving demand for low-carbon materials**.

Sources: ACA, Roadmap to Carbon Neutrality (2025); FCA, Cement Value Chain (2024); RMI, Insights on cement industry's net zero transition (2023); PCA, Roadmap to carbon neutrality (2024).
Credit: Beatrice Klein, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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Financing, operating, and stakeholder barriers are preventing the adoption of low-carbon cement and concrete

Financing

High CapEx and limited financing options

- **Greenfield plants will be capital intensive.** A new U.S. cement plant at 1+ MTPA commercial scale can require ~$0.5 billion to $1 billion in CapEx per deployment.
- Major investments are typically financed on the balance sheet with **limited use of project finance.**

Lack of long-term offtake agreements

- Ready-mix companies and contractors purchase on an as-needed basis and are **reluctant to commit to longer term offtake** due to uncertainty about long-term demand **amidst boom-and-bust construction market cycles.**
- This makes it **challenging to create a credible long-term demand signal** for the scale-up of new technologies for low-carbon cement.

Operating

Technological uncertainty

- Measures such as CCUS or alternative production methods for low-carbon cement have **not been tested 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 at scale.

Lack of standard process and limited data

- There is **no single standard methodology** to assess the embodied carbon of products, making it **challenging to compare cements and concretes during a competitive procurement process.**
- **Lack of robust emissions data** for specific inputs and production makes it challenging to conduct standardized environmental product declarations.

Stakeholder

Risk aversion and long adoption cycles

- The cement sector has a **~10- to 20-year adoption cycle** for new blends and materials — both from the **long lead time to update standards** and a **long customer adoption cycle.**
- Contractors, engineers, and ready-mix companies are **risk-averse to adopting new technologies** that may lead to budget and schedule overruns or safety risks.

Complex intermediaries

- Approximately **96% of all cement shipped goes through intermediaries.**
- The value chain is **highly fragmented at intermediary tiers** between cement manufacturers and large buyers such as government procurement.

Source: DOE Liftoff Report, Low carbon cement (2023).
Credit: Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

High CapEx and long horizons mean climate hard-tech startups must overcome technological and commercial 'Valleys of Death'

Overcoming the first valley involves technological de-risking; the second requires proof of commercial viability and bankability of hard-tech solutions

		Technological Valley of Death		*Commercial Valley of Death*	
Product stage	**1 Lab development**	**2 Pilot factory**	**3 Commercial-scale testing**	**4 FOAK[1] plant**	**5 SOAK* plant**
Size of tech	1 small reactor	Multiple small reactors *(e.g., 5x)*	1 big reactor	Multiple big reactors *(e.g., 20x)*	Multiple big reactors *(e.g., 100x)*
System layout	Small system, testing technology	Integrated system with real process conditions	Larger engineering validation	Full integrated commercial plant	Replicated commercial plant
Proof of concept	Technology	**Technical scalability**	Commercial size technology	**Commercial scalability and profitability**	Commercial returns
Expected IRR	n/a	Negative IRR	n/a	High teens to 25%	n/a
Capital costs[2]	$1M-$20M	$5-$40M	$20-$100M	$100M-$1B	Similar to FOAK but lower unit costs

Observations

- The two valleys are qualitatively different: the technological valley is a capital availability problem (negative IRR, no debt possible); the commercial valley is a risk-return mismatch (VC-level risk, infra-level returns).
- Have elaborate development and testing process with high capital costs due to the hard-tech character of climate start-ups.
- Capital scales ~5x to 10x at each stage; the largest absolute jump is to FOAK ($80M-$900M in a single step), when project finance is often not available yet.
- The FOAK range ($100M-$1B) is the widest of any stage, reflecting sector variation.
- Stages 1 and 3 show no IRR because they are funded from the corporate balance sheet: no standalone investment case yet.
- "High teens to 25%" at FOAK reflects investor required rates, not realized returns — often a hurdle to obtaining investments.

[1]FOAK = first of a kind; SOAK = second of a kind. [2]Capital costs refer to construction CapEx only; excludes OpEx, financing costs, and pre-FID development expenditure.

Sources: DOE, Learning from Case Studies: Financing and Development Approaches from Recent First-of-a-Kind Projects (2024); Sightline Climate, Meet the FOAK folks (2025); Extantia Capital, The FOAK Question: Essential Insights for Financing and Planning First-Of-A-Kind plants (2023).

Credit: Soraya van Beek, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

Capital efficiency key to overcoming technological Valley of Death; risk transfer across value chain key for commercial valley

Climate-tech startups must de-risk demand and often leverage public, concessional, or philanthropic capital to finance FOAK* commercial plants

1 Bench-scale testing → 2 Pilot factory → 3 Commercial-scale testing → 4 FOAK* plant → 5 SOAK* plant

Technological Valley of Death (2 Pilot factory)

- **Reduction of capital needs** by keeping team light and using existing equipment and materials (not reinventing every step in process).
- **Partnerships without equity**, to develop pilot scale and establish first relationships for offtake agreements (hyperscalers often have the capital and risk appetite).
- **Government grants/loans**, which should be politically agnostic (e.g., independence rather than climate).

Commercial Valley of Death (4 FOAK* plant)

- **Offtake agreements**, to prove demand to secure potential project finance.
- **Tailored niche product** instead of diversification (e.g., high-quality iron instead of high-volume steel)
- **Integration in established value chain** with experienced partners for supply and construction.
- **Government grants and loans.**

Climate-tech start-ups are **forced to self-develop and build their own plants** because unproven technology and high construction risk make it impossible to find a licensing partner; only once commercial viability is demonstrated can they transition to the higher margin role of equipment provider or licensor.

Observations

- The technological valley solutions are primarily about capital efficiency: reducing what you need to spend; the commercial valley solutions are about risk transfer: shifting risk onto counterparties (offtakers, value chain).
- Government grants are equally critical at the commercial valley: DOE/EU funding has been an enabler of FOAK project debt in recent cases (e.g. Stegra, LanzaJet).
- "Tailored niche product" is a highest risk commercial strategy: It narrows the customer base, but protects margin if it works.
- High-risk construction often leads to companies turning to in-house development.
- The two solution sets are sequentially dependent.

[1]FOAK = first of a kind; SOAK = second of a kind. [2]Capital costs refer to construction CapEx only; excludes OpEx, financing costs, and pre-FID development expenditure.

Sources: DOE, Learning from Case Studies: Financing and Development Approaches from Recent First-of-a-Kind Projects (2024); Sightline Climate, Meet the FOAK folks (2025); Extantia Capital, The FOAK Question: Essential Insights for Financing and Planning First-Of-A-Kind Plants (2023).

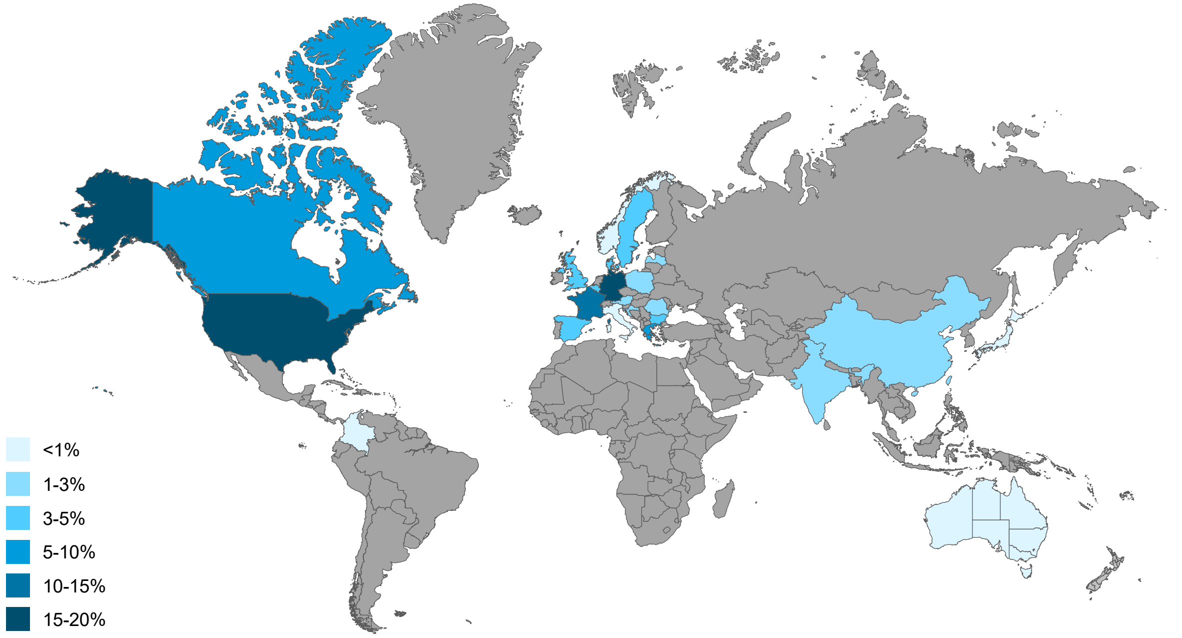
Other industries with high CapEx and long horizons underscore the need for structural mechanisms to overcome Valley of Death

	Solar 1.0	Pharmaceuticals & Biotech	Defense & Aerospace
Description of Funding Challenge	- Until 2000s, solar panels were uncompetitive vs. fossil fuels. - Manufacturers had no independent buyers at utility scale. - Government R&D alone couldn't create commercial demand.	- Pharma R&D costs between \$0.3B and \$2.6B per drug. - 10- to 15-year timeline - ~90% failure rate - Biotech startups burn cash for years pre-revenue, with no guarantee of approval.	- Major defense developments cost \$10B to \$50B+ per platform. - 10- to 20-year development - Companies often have only a single buyer (government).
Solution Approach to Valley of Death	- Government "feed-in tariffs“ guaranteed 20-year revenue, converting unproven tech into bankable assets. - Manufacturers like First Solar and SunEdison built their own first utility-scale plants to prove the technology. - Learning curve showed that costs fell ~20% to 24% per doubling of capacity.	- FDA phase gates (I → II → III) create staged value inflection points, each unlocking new investor classes. - Big Pharma acquires/licenses at each gate. - NIH funds ~\$47B/year in early research. - Risk becomes tradeable.	- Government is the customer *and* the co-developer. - Cost-plus contracts eliminate financial risk during R&D. - Multi-decade procurement guarantees revenue before production
Context Similarity	High	Medium	Medium
Learnings for Climate Tech	Long term off-take guarantees foster “bankability.”	Structured de-risking steps needed to unlock new capital classes.	Government must recognize climate change mitigation as national security objective.

Sources: DOE OECD, Learning from Case Studies: Financing and Development Approaches from Recent First-of-a-Kind Projects (2024); U.S. GAO, F-35 Sustainment (2021); CBO, Research and Development in the Pharmaceutical Industry (2021); Bolinger et al., Levelized cost-based learning analysis of utility-scale wind and solar in the US (2022); Jones and Bouamane, A Business History of Solar Energy (2012).
Credit: Paul Greitemann, Soraya van Beek, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner et al., “Decarbonizing Cement” (16 July 2026).

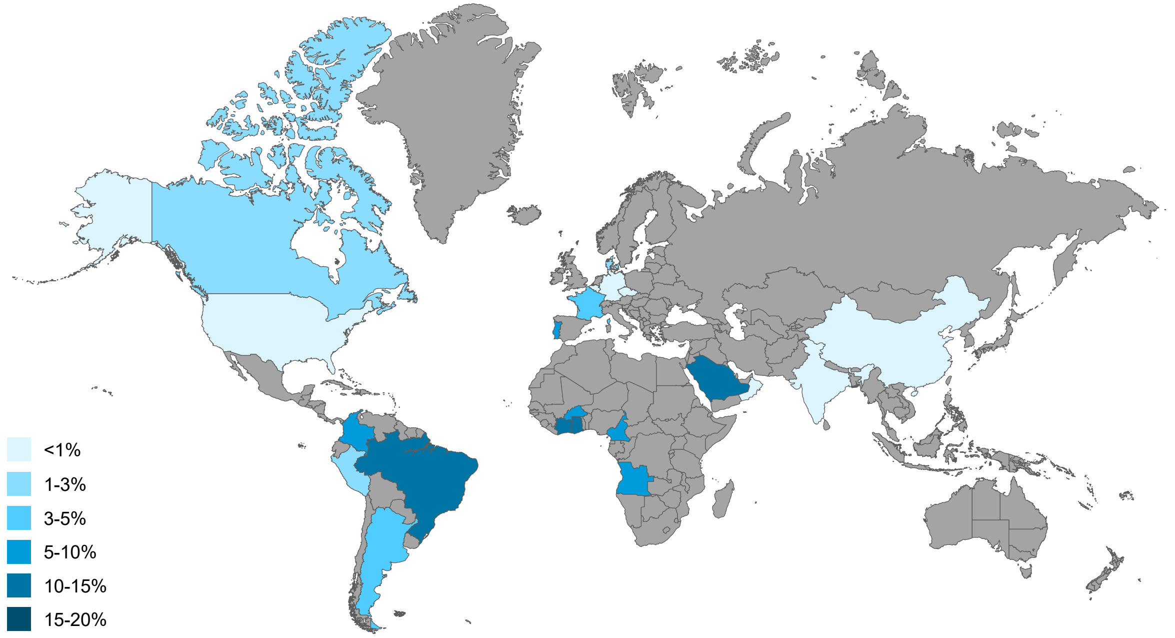
Investment capacity and infrastructure drive CCUS in Global North; clay reserves and capital constraints drive LC3 in South

Cement CCUS capacity[1], global distribution, *Dec. 2024*



- **North America and the EU account for 92%** of stated capacity from announced cement CCUS projects.
- **High capital needs and strong policy support** (e.g., U.S. 45Q tax credit) drive CCUS deployment in high-income countries.
- **Existing oil and gas infrastructure** in developed markets (e.g., pipelines, storage facilities, geological data) enable faster rollout. For example, Norway's Northern Lights project uses existing North Sea oil infrastructure to store CO_2.

Clay calciner capacity[1], global distribution, *Dec. 2024*



- **Africa** accounts for **44%** of stated capacity from announced clay calciner projects.
- Clay calcination kilns are **less capital intensive** and easily integrated into existing cement plants than CCUS installations, making them a more attractive option for countries with limited industrial investment capacity.
- Many developing countries have **abundant clay reserves** but rely on imported clinker due to the scarcity of high-grade limestone. Clay-based alternatives offer a **cost-effective solution** to meet rising cement demand amid rapid urbanization in developing countries.

[1] Expected at full operation based on stated disclosed carbon capture capacity for CCUS and stated disclosed installed capacity for clay calciner.
Source: GCCA and LeadIT, Green Cement Technology Tracker (2024).
Credit: Adele Teh, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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A broad range of policy instruments have been implemented to decarbonize cement manufacturing

Enablers	Policy type	Policy instrument	Key examples	Impact
Risk management	Risk-sharing	Financial certainty to innovators (through subsidy and incentives)	• EU Carbon Contracts for Difference • U.S. DOE's Industrial Demonstration Program	Provides financial certainty to innovators by sharing investment risks in early-stage low-carbon technologies, incentivizing adoption and de-risking the transition to decarbonization solutions.
Technology	Incentive-based	R&D direct funding	• EU Innovation Fund	**$800 million** funding for six cement CCUS projects in the EU.
		Supporting regulations	• EU Net-Zero Industry Act	Strengthens regulations and creates an enabling environment to boost CCUS technology development and stimulate investments; currently in the proposal stage.
	Market-based	Carbon price	• EU ETS • California ETS • China ETS (announced, not formalized)	Incentivizes cement producers to reduce emissions.
		Border adjustment tariff	• CBAM (pending implementation) • Prove It Act (under discussion)	Emission-intensive cement exporters to the EU face a cost escalation of up to 100%; needs to be complemented by transparent and carbon accounting standards.
Demand	Incentive-based	Green public procurement (GPP)	• GPP concrete product policies in Germany, the Netherlands, the UK, and Sweden • Federal Buy Clean Initiative in the U.S. • Key cement producers as IDDI members (UK, India)	Creates a viable market for low-emission cement through GPP commitments.
	Mandate-based	Building/end-use product codes and standards	• Embodied carbon limit policies in the Netherlands, Sweden, France, and Germany • U.S. General Services Administration low embodied-carbon concrete standards in the U.S.	Provides a clear market signal to low-emission cement production.
Infrastructure	Incentive-based	CCUS infrastructure direct funding	• Public funding of CCUS hubs in the EU • CCUS hubs provision under Bipartisan Infrastructure Law	Over **$6 billion** committed to develop CCUS hubs in the U.S. and EU.
Capital	Incentive-based	Tax credits/subsidies	• CCUS tax credits under IRA and OBBBA	**20% to 30%** reduction in costs to deploy CCUS in cement plants.

Sources: WEF, Industry NZ tracker (2023); EU, Innovation Fund (2024); EU, Net-Zero Industry Act (2024); EU, ETS (2024); ICAP, California ETS (2024); EU, CBAM (2024); Office of Sustainability, Federal Buy Clean Initiative (2024); S&P, IRA 45Q (2023); CATF, CCfDs (2023); DOE, Industrial Demonstrations Program (2023).
Credit: Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

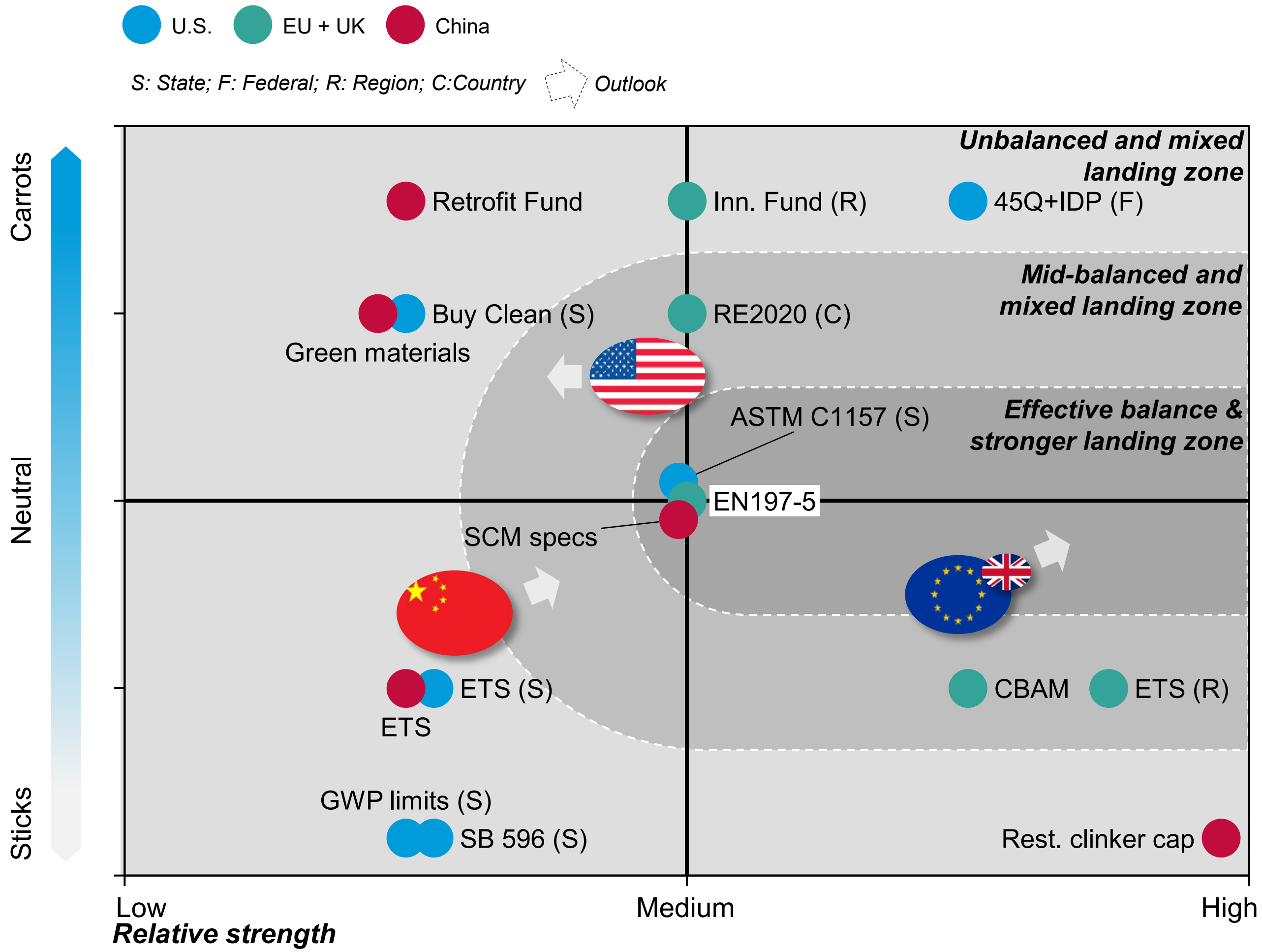
U.S., China, and EU + UK have deployed policies across the full carrots-sticks spectrum to incentivize cement decarbonization

Policy type		United States	EU and UK	China
		2023: 40 $MtCO_2$ World Rank: 5th	2023: 71 $MtCO_2$ World Rank: 3rd	2023: 718 $MtCO_2$ World Rank: 1st
Carrots — **Push**	Improve project economics of cement decarb tech (credits, grants, concessional finance).	• IRA 45Q **tax credit for CCS** since 2023, preserved under OBBBA.	• **Innovation Fund:** 16 cement projects have been funded. • Carbon **CfD pilot.**	• **Green Credit Guidelines** (updated 2021). Banks prioritize lending to green investments including green cement.
Pull	Incentivize demand via procurement, disclosure, or embodied carbon rules.	• **Buy Clean** (federal/state) in 2021. • Public procurement guarantees demand. Federal canceled in 2025.	• National Embodied Carbon Disclosures (e.g., France RE2020) binding since 2021. Creates demand for verified low-carb cement.	• GB/T Green Building Code (MOHURD ’17+, revised ’20). **Green materials in public projects. Pulls low-carb cement.**
Neutral — **System enablers**	Remove barriers via standards, codes, or infrastructure, to allow for new materials and supply chains.	• States’ **DOT adoption of ASTM C1157** (Performance Cement Spec). Removes prescriptive clinker limits.	• EN 197-5 Standard – CEN 2021. Active. **Approves calcined clay (LC3) blends**, enables clinker substitution.	• **GB 175-2023 and related SCM specs** (GB/T 1596; GB/T 18046) legally define types and allow lower-clinker compositions.
Penalize	Internalize externalities by raising costs or removing negative existing incentives.	• **California Cap-and-Trade Program** (CARB, since 2013). Impact: Adds ~\$2 to \$35/tCO_2 to clinker cost. • **RGGI C&T:** \$1.5B revenues in ’24.	• **EU ETS Phase IV and CBAM phase-in 2023-26.** Tightens free allocation; border tariff raises cost of carbon-intensive imports.	• National ETS **expansion to cement; first compliance end of 2025.** Absolute caps signaled for 2027.
Sticks — **Prohibit**	Legal bans or caps on fuels, clinker, or emissions.	• Colorado **DOT GWP caps for cement and concrete**, Jan. 1, 2025; applies to projects with construction on or after July 1, 2025.	• UK coal phase-out (BEIS, binding 2025). **Cement kilns must shift away from coal fuels.**	• **No new clinker capacity and strict capacity replacement (2024).** Tougher replacement ratios (e.g., ~2:1 in air-polluted regions).

Sources WEF, Industry NZ tracker (2023); EU, Innovation Fund (2024); EU, Net-Zero Industry Act (2024); EU, ETS (2024); ICAP, California ETS (2024); EU, CBAM (2024); GPP Pledge (2023); Office of Sustainability, Federal Buy Clean Initiative (2024); S&P, IRA 45Q (2023); EU; CCfDs (2024); DOE, Industrial Demonstrations Program (2023); Chinese Standards, Common Portland cement (2023); Global Carbon Atlas, Carbon Emissions (2023); ICAP, China ETS (2024); Reuters, China’s bank to extend carbon lending tool (2024); Colorado DOT, Buy Clean Colorado Act (2025); ICAP, USA - (RGGI) (2025).

Credit: Nicolas Herrera Isaza, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., “Decarbonizing Cement” (16 July 2026).

EU + UK and China are tightening restrictive policies; U.S. is pulling back on incentive-based support



U.S.: Carrots being removed, few and weak sticks

- Moderate mix of carrots and sticks. Relative to the EU and China, the U.S. offers more carrots and puts less pressure on companies.
- Large push incentives (e.g., 45Q \$85/ tCO_2e + IDP) support limited number of projects.
- **Carbon pricing is limited to a few states** (i.e., 13 states[1]) ~\$30/ tCO_2.
- Outlook relaxes policies' strength.

EU + UK: Strong sticks, need stronger incentives

- Lean heavily on sticks; low balance score but high strength.
- Carbon **prices around €79/t.**
- CBAM ('26) **closes carbon leaks.**
- Innovation Fund just covered **16 cement projects for ~€2.4B vs. ~€180B** in revenue for ETS.
- **Uneven lower clinker content standards** adoption (EN197-5).
- Strengthening at a slower pace.

China: Refreshed ambitious NDC

- China's mix features **strict capacity caps (1.8B ton)** but low carbon prices and diffuse financing.
- Low direct funding, but new construction standards permit SCMs.
- Strong national plans target 30% of cement capacity to reach benchmark energy efficiency[1] by 2025.
- ETS now covers cement. Price ~\$13 per ton.
- New ambitious NDC → outlook is positive.

[1] States include California, Oregon, Washington, Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont.

Sources: WEF, Industry NZ tracker (2023); Climate Bond Initiative (2023); EU, Innovation Fund (2024); EU, Net-Zero Industry Act (2024); EU, ETS (2024); ICAP, California ETS (2024); EU, CBAM (2024); GPP Pledge (2023); Office of Sustainability, Federal Buy Clean Initiative (2024); S&P, IRA 45Q (2023); EU; CCfDs (2024); DOE, Industrial Demonstrations Program (2023); Chinese Standards, Common Portland cement (2023); Global Carbon Atlas, Carbon Emissions (2023); ICAP, China ETS (2024); Reuters, China to extend carbon lending (2024); Colorado DOT, Buy Clean Colorado Act (2025); C2ES, US state carbon pricing (2025); Global Cement, EU funds 14 projects (2025); EU, ETS (2025); China Briefing, China's CO2 reduction plan (2024); Climate Bonds, China's green finance catalogue (2025).

Credit: Nicolas Herrera Isaza, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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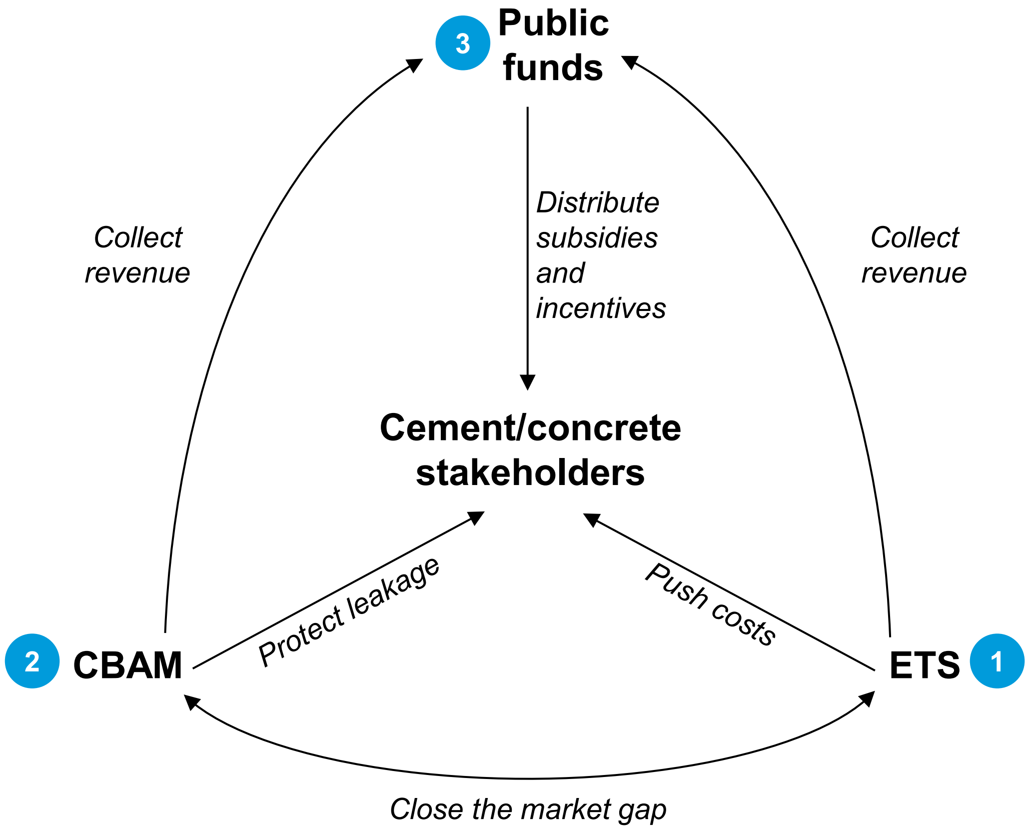
EU incentivizes decarbonization through ETS, CBAM, and public funding; push, protect, and pull mechanisms to that end

EU policy tools to incentivize decarbonization



1 EU Emission Trading System (ETS)

- Primary carbon pricing mechanisms are pushing costs to emitters.
- With free allowances starting to phase out in 2026 and falling to 0% in 2034, carbon prices are expected to surge.
- Costs may increase 80% by 2034 for cement companies.
- Program significantly strengthened since ETS Phase I through tighter caps, reduced free allocation, and structural reforms.
- Market Stability Reserve (MSR, 2019) adjusts allowance supply to limit surplus and stabilize prices.

2 EU Carbon Border Adjustment Mechanism (CBAM)

- Aims to avoid carbon leakage due to imports coming from places with lower or no carbon costs (taxes or ETS).
- Applied to certain imported goods, including cement.
- Introduced originally in 2023. The levy phase-in will start in 2026 and be fully operational in 2034.

3 EU Public Funding

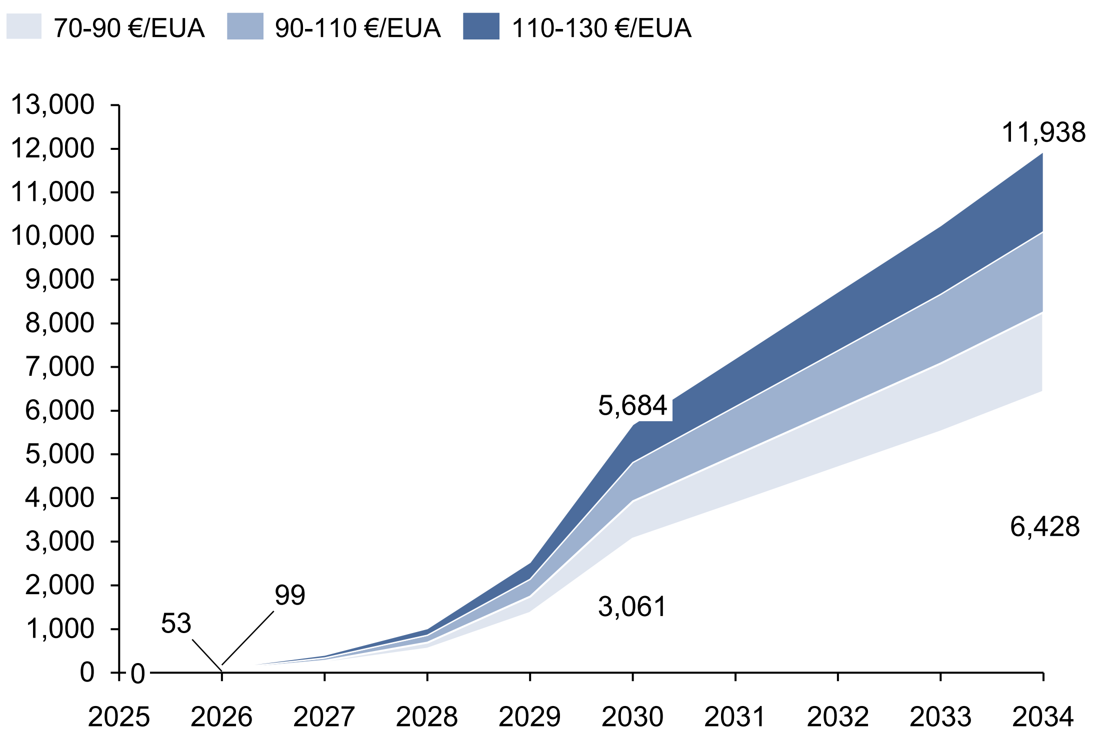
- Up until 2023, member countries were expected to allocate at least 50% of ETS auctioning revenues toward climate and energy. In 2024, that expectation increased to 100%.
- REPowerEU and the EU Innovation Fund are among the programs whose revenues are being directed toward decarbonization.

Sources: BCG, Decoding ETS and CBAM (2025); European Environment Agency, Use of EU ETS revenue (2024).
Credit: Nicolas Herrera Isaza, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner et al., “Decarbonizing Cement” (16 July 2026).

As EU ETS free allowances phase out, carbon is projected to represent ~30% to 50% of cement costs by 2034

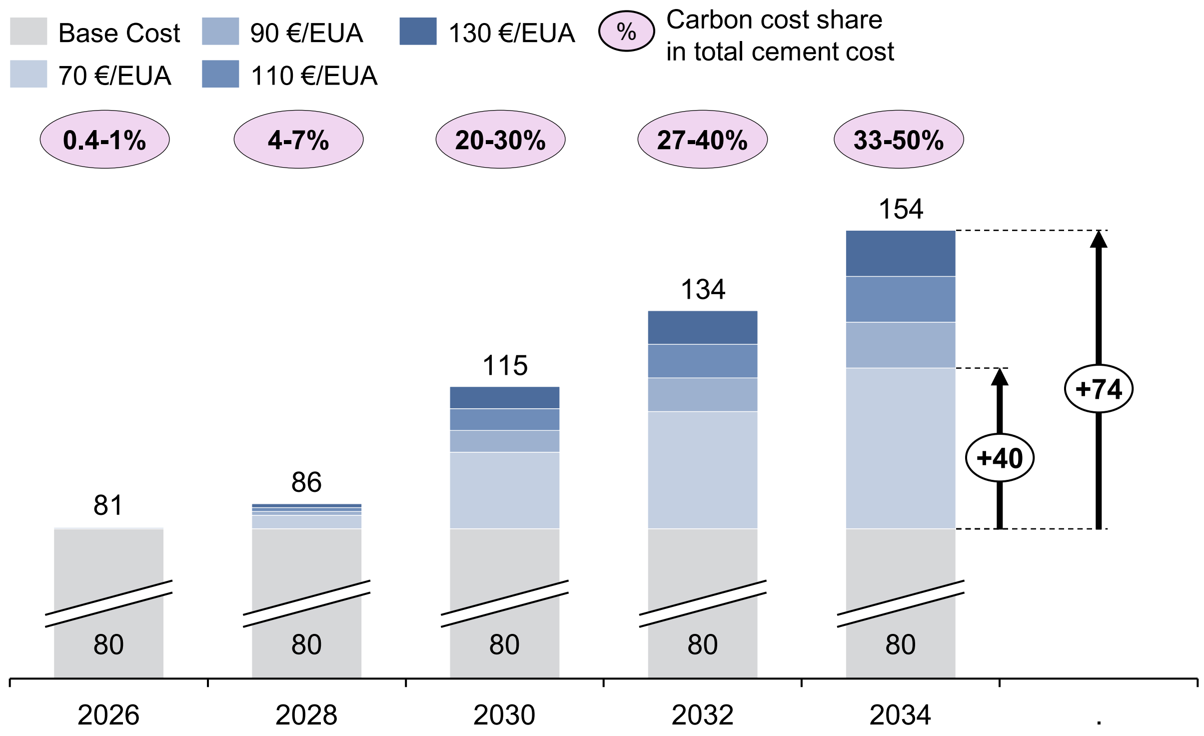
Even in a conservative scenario, total allowance costs to the cement industry will see a sharp increase by 2034

ETS total allowance costs scenarios for cement industry, *€ million*



Total cement costs could increase by ~50% to 100% by 2034 due to carbon pricing alone

Incremental carbon pricing impact over cement costs, *€/t of cement*



Assumptions: Emissions intensity 0.57 tCO2e/t cement as benchmark; stable cement consumption (production-exports+imports) at 160 Mt/year
Sources: CKI analysis; BCG, Decoding ETS and CBAM (2025); European Environment Agency, Use of EU ETS revenue (2024).
Credit: Nicolas Herrera Isaza, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner et al., “Decarbonizing Cement” (16 July 2026).

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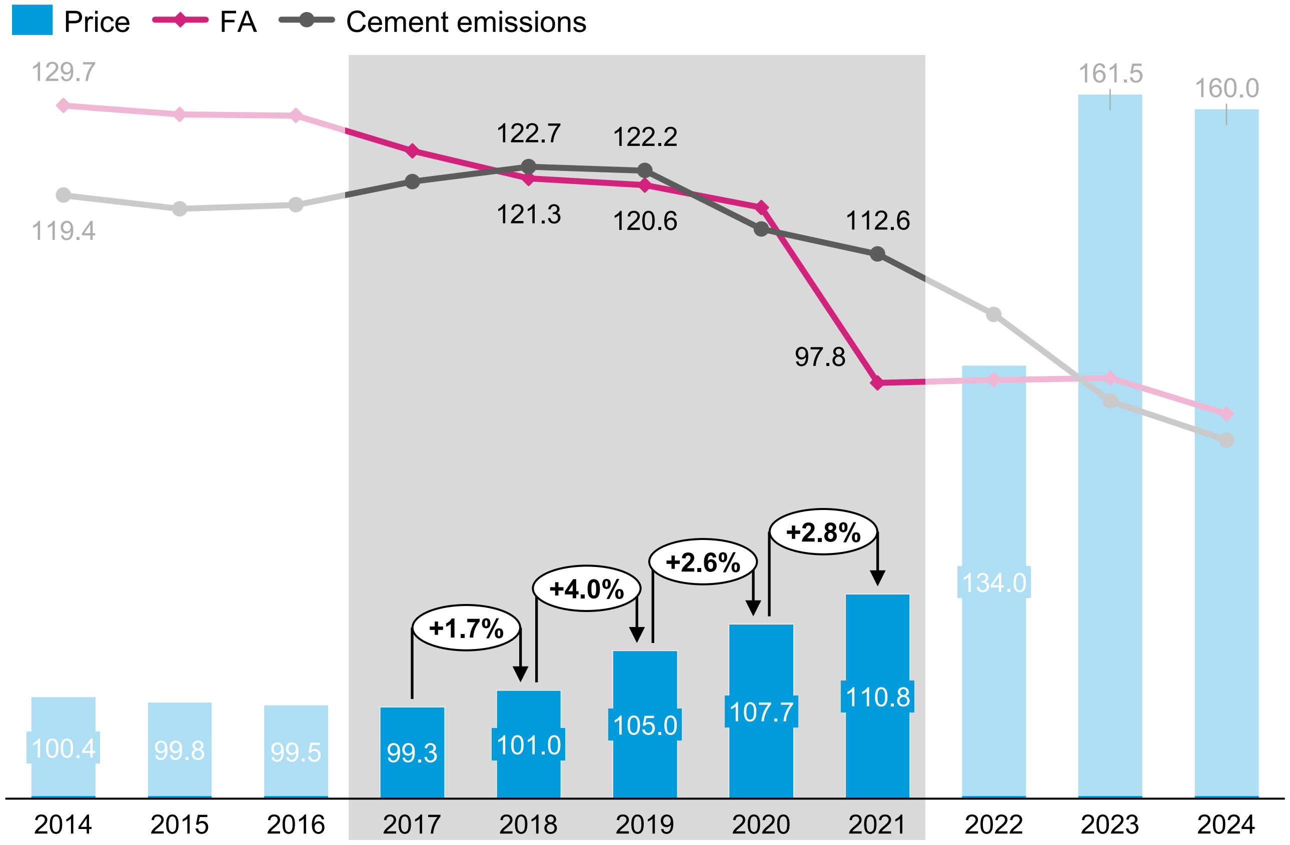
EU high cement prices are mainly driven by energy costs but show a correlation with the free allowances decrease from 2017 to 2021

EU ETS cement free allowances vs. cement emissions vs. cement prices, *million tCO_2e, €/t of cement*



ETS sticks likely contributed to an **increase in cement prices.**

FA phase-out + CBAM phase-in will likely keep **cement prices high**…

…if **low- or positive-cost abatement solutions** are not supported (i.e., balancing carrots).

Observations

- **In 2021, for the first time since ETS started, free allowances for cement were below the industry's total emissions.**
  - Before the benchmark adjustment, cement companies were able to make profits from the free allowances they were given.
  - In 2018, ETS primary market prices were on average at €15.5 per tCO_2e, but in the same year, prices reached almost €25 per tCO_2e — a historic maximum.
- **At the same time, cement prices increased by ~2.8% per year, which meant a jump of ~11.5% in four years.**
- **While there was already a decreasing trend coming from 2016, 2017 through 2021 saw a 40% contraction in cement exports and 3x growth in imports.**

[1] Cement companies were able to sell free allowances and make a profit of around €2 billion between 2008 and 2015. The ETS has since significantly tightened, leaving little to no room.

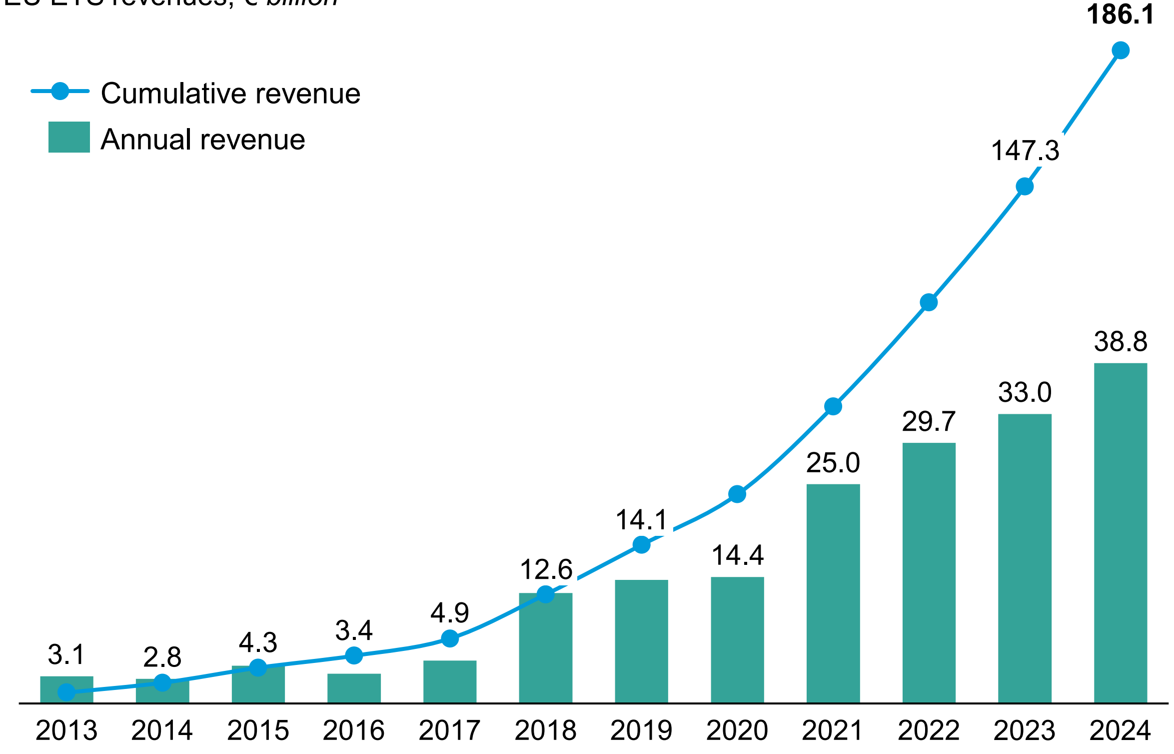
Sources: CEMBUREAU, EU cement industry trade statistics (2025); Trading Economics, EU producer prices: manufacture of cement (2025); Global Cement, EU funds 14 cement projects (2025); Global Cement, EU Innovation Fund (2025); Carbon Market Watch, Cement pollution windfall from EU ETS (2016); WWF, Clean industrial revolution in Europe (2025); EEA, EUU ETS data viewer, (2025); International Carbon Action Partnership (2025).

Credit: Nicolas Herrera Isaza, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

ETS revenues have reached €180B since 2013; of that, just ~€31B has been allocated to EU's Innovation and Modernization funds

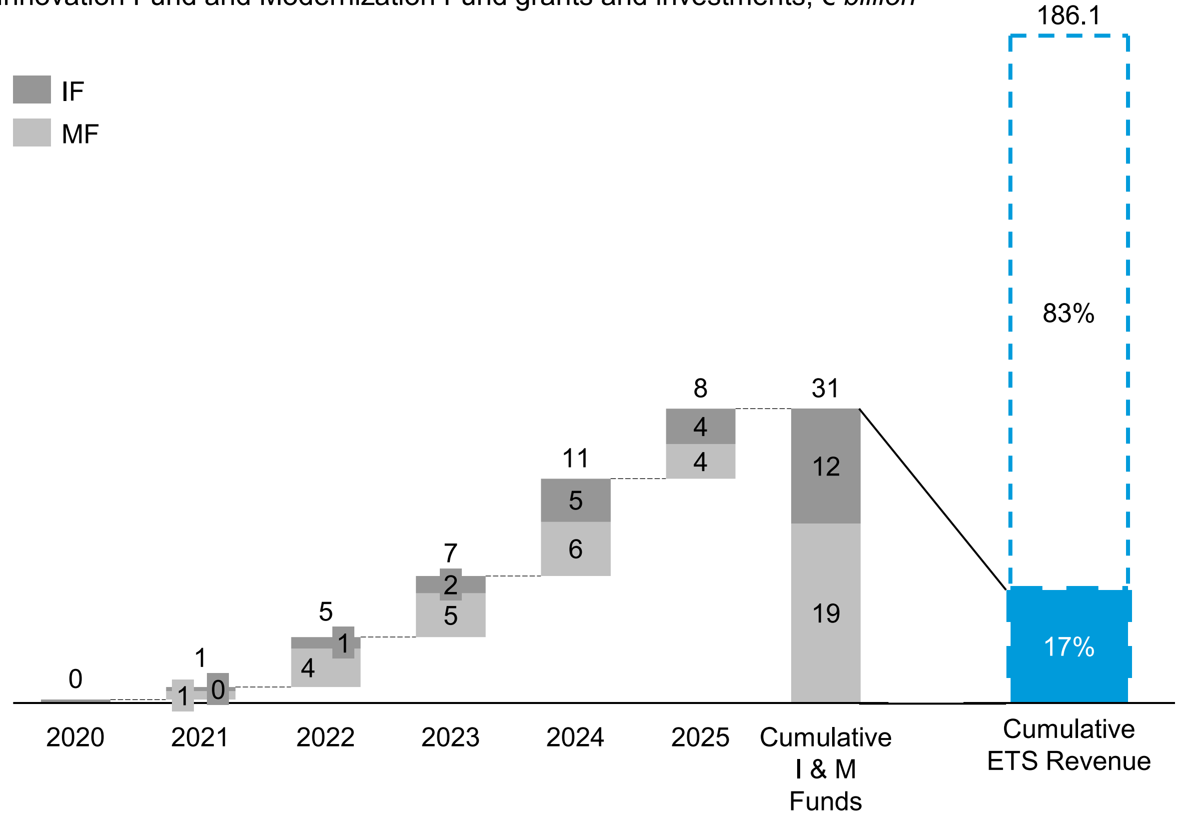
In 2024, EU ETS collected €38B as carbon prices grew and allowances tightened …

EU ETS revenues, € *billion*



… but only 17% of cumulative revenue has gone to IF[1] and MF[2], which earmark EU investments for climate[3]

Innovation Fund and Modernization Fund grants and investments, € *billion*



[1] EU Innovation Fund. [2] EU Modernization Fund. [3] Most revenue goes to member countries, which are required to allocate it toward climate purposes. Since 2024,100% of the revenues given to countries should be used for climate action, including social costs of climate change.

Sources: EU, Innovation Fund (2024); EU, Modernisation Fund (2024); EEA, Use of EU ETS revenues (2024); European Commission, Auctioning of allowances (2025).

Credit: Nicolas Herrera Isaza, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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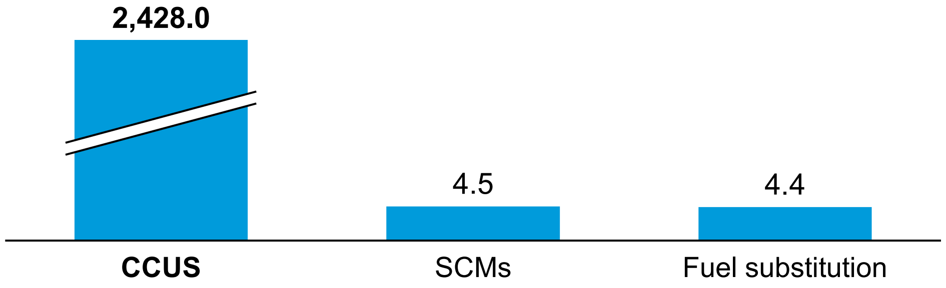
Cement contributed little to ETS revenues but received ~20% of the Innovation Fund's contributions — its greatest beneficiary

EU GA[1] IF contributions, *€ billion*

	EU GA IF contributions, € billion	*# projects*	*Avg. €/project*
Cement & lime	**2.4**	**16**	**€152,3**
Hydrogen	2.2	34	€63,6
Chemicals	1.7	23	€73,8
Other	1.1	14	€75,5
Manufacturing components for RE or BESS	0.9	14	€65,1
Refineries	0.9	15	€58,8
Iron & steel	0.7	8	€93,7
Other 18	2.4	93	€25,5

99.9% of funds target CCUS projects, one of the highest cost solutions for cement decarbonization

Innovation Fund and Modernization Fund grants and investments, € *million*



	CCUS	SCMs	Fuel substitution
Germany	€686,6		
France	€398,6		
Greece	€358,3		
Belgium	€230,0		
Poland	€228,2		
Denmark	€220,1		
Bulgaria	€189,7		
Croatia	€116,9		
Spain		**€4,4**	**€4,5**

Higher allocations due to **large pipeline of ETS-exposed, investment-ready industrial projects**

[1] GA: Grant agreements.

Source: EU, Innovation Fund (2024).

Credit: Nicolas Herrera Isaza, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

New York State's Buy Clean Concrete guidelines mandate environmental standards (EPDs) and set GWP limits for concrete

New York State’s Buy Clean Concrete guidelines

Section	Explanation
Environmental standards (EPDs)	• Mandatory Environmental Product Declarations (EPDs) are required for all concrete mixes starting Jan. 1, 2025. These guidelines quantify the environmental impact of products over their lifecycle.
Who does this affect?	• State agency projects over $1 million. • Department of Transportation projects over $3 million.
Emission limits (GWP)	• Specifies GWP (global warming potential) limits for concrete, expressed in CO_2e (carbon dioxide equivalent), with adjustments planned post-2026.
Timeline	• Phase 1 (2024): Voluntary GWP and EPDs • Phase 2 (2025-2026): Mandatory compliance and certification • Phase 3 (post-2026): Revised GWP limits

Minimum emission limits for concrete

Compressive strength (PSI)	Maximum emission limits (kg CO_2e per cubic yard)
0 – 2500	275
2501 – 3000	302
3001 – 4000	360
4001 – 5000	434
5001 – 6000	458
6001 – 8000	541

Source: NYS, Buy Clean Concrete Guidelines (2023).
Credit: Hoshi Ogawa, Sho Tatsuno, Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., “Decarbonizing Cement” (16 July 2026).

The New York cement supply chain faces regulatory constraints, high energy consumption, logistics costs, and market pressures

Supply chain stages and pain points

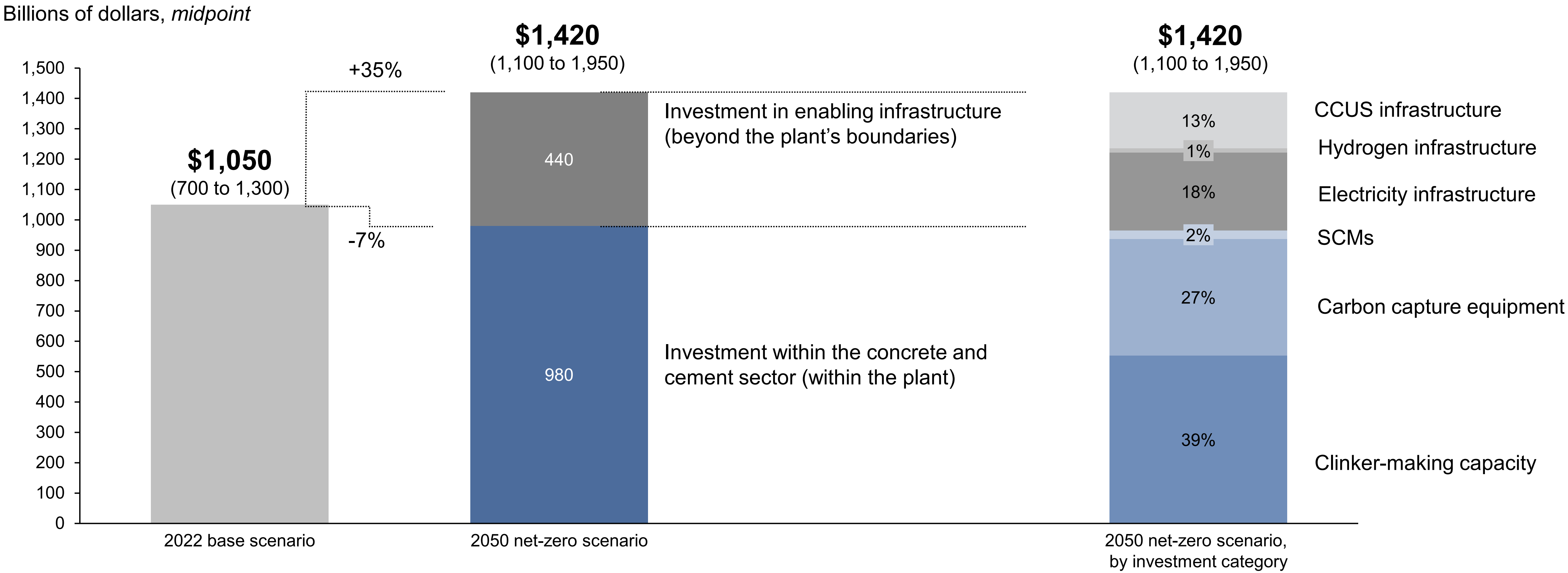
Extraction & Raw Materials	Manufacturing	Distribution	Sales & Market Demand	End Use & Application
• Environmental degradation. • Regulatory constraints on land use. • Fluctuating quality of raw materials.	• High energy consumption and carbon emissions, especially in clinker production. • Aging infrastructure, leading to inefficiencies. • Compliance with stringent environmental regulations.	• Logistics costs, impacted by fuel prices and infrastructure limitations. • Emissions from transportation. • Supply chain disruptions.	• Competitive market pressures. • Sensitivity to economic cycles affecting construction demand. • Navigating state-specific requirements like New York's low embodied carbon concrete regulations.	• Ensuring product performance under diverse environmental conditions. • On-site storage and handling issues. • Adapting to innovative building practices and materials.

Source: NYS, Buy Clean Concrete Guidelines (2023).

Credit: Hoshi Ogawa, Sho Tatsuno, Shailesh Mishra, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

Delivering a net-zero future requires a 35% increase in investment to develop necessary enabling infrastructure

Cumulative investments, projected 2022 to 2050



Sources: Mission Possible, Making net-zero concrete and cement possible (2023); GCCA, Concrete future: Roadmap to net zero (2021).
Credit: Shailesh Mishra, Jessica Cong, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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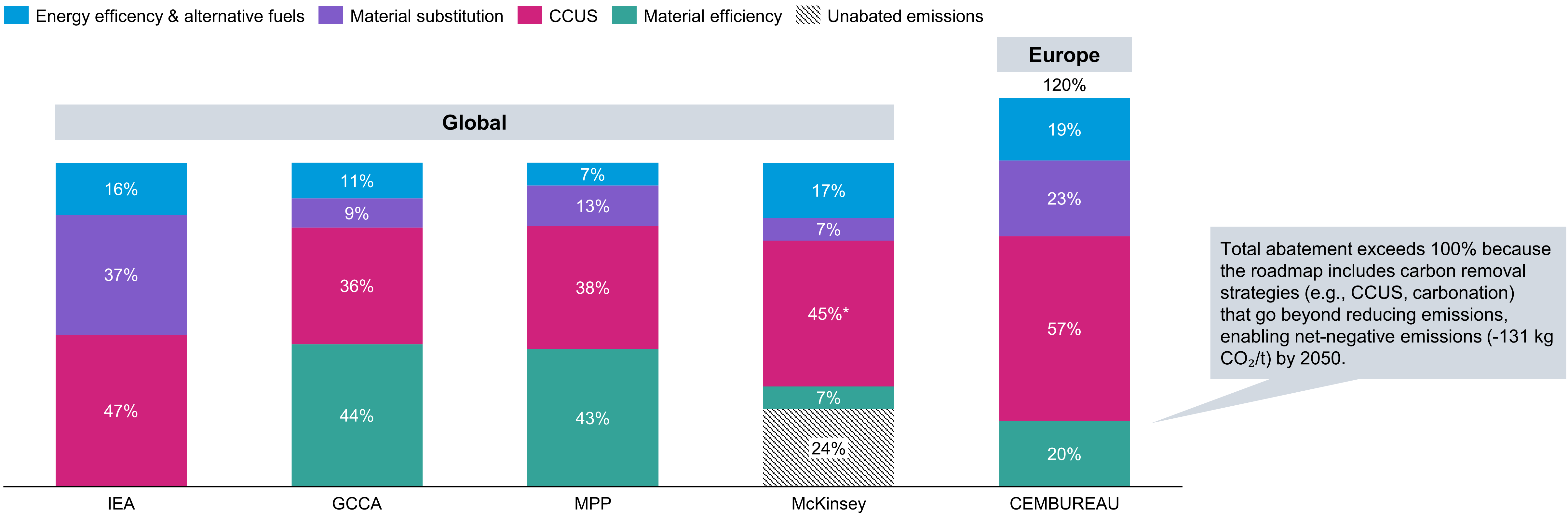
Different roadmaps consider efficiency, material substitution, and CCUS as key decarbonization levers, with CCUS abating ~36%-50%

Comparison of global cement and concrete decarbonization levers by 2050

Percentage share of CO_2 emissions abated by key levers



Sources: DOE, Pathways to Commercial Liftoff (2023); GCCA, Concrete future: Roadmap to net zero (2021); McKinsey, Zero-carbon cement (2020); ClimateWorks Foundation (2021); CEMBUREAU, From Ambition to Deployment (2024).
Credit: Beatrice Klein, Isabel Hoyos, Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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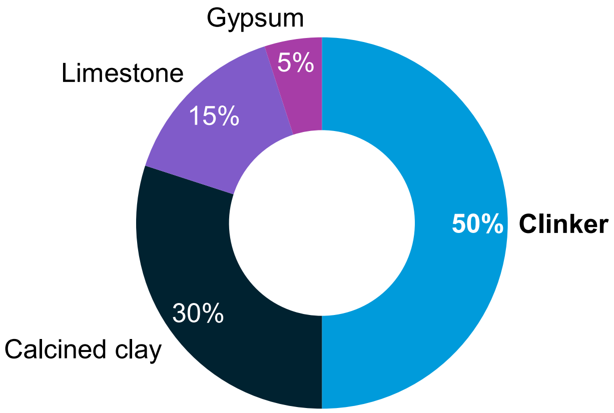
Appendix

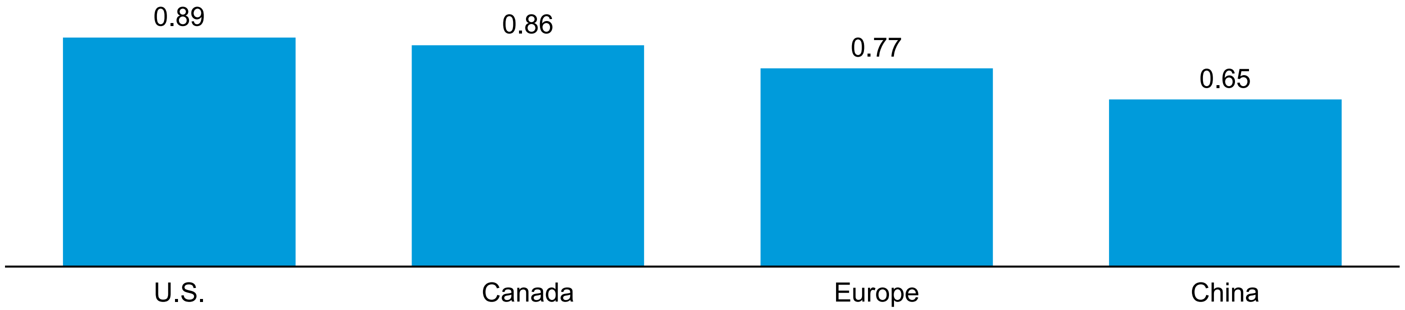
Blended cements partially replace clinker, reducing emissions with just minor changes to the production process or added costs

Limestone calcined clay cement (LC3): Leading blended cement



- **40% less CO_2 emissions**
- **Enhanced durability and performance**
- **25% lower overall costs**
- **Accelerating global adoption**

Clinker-to-cement ratios vary considerably by region, latest available:



Observations

- **Blended cements** partially substitute clinker with **supplementary cementitious materials (SCMs).**
- **Limestone calcined clay cement (LC3)** is a leading blended cement offering a viable pathway to decarbonize the cement industry.
  - **LC3 has a clinker ratio of 0.5.**
  - Compared with ordinary Portland cement, it has **40% less CO_2 emissions** and **25% lower overall costs.**
  - **Lower processing temperatures:** Calcining clay requires flame temperatures of 690-800ºC, much lower than that required by traditional clinker.
- Clinker-to-cement ratios vary considerably by region due to **material availability and local regulations.**[1]

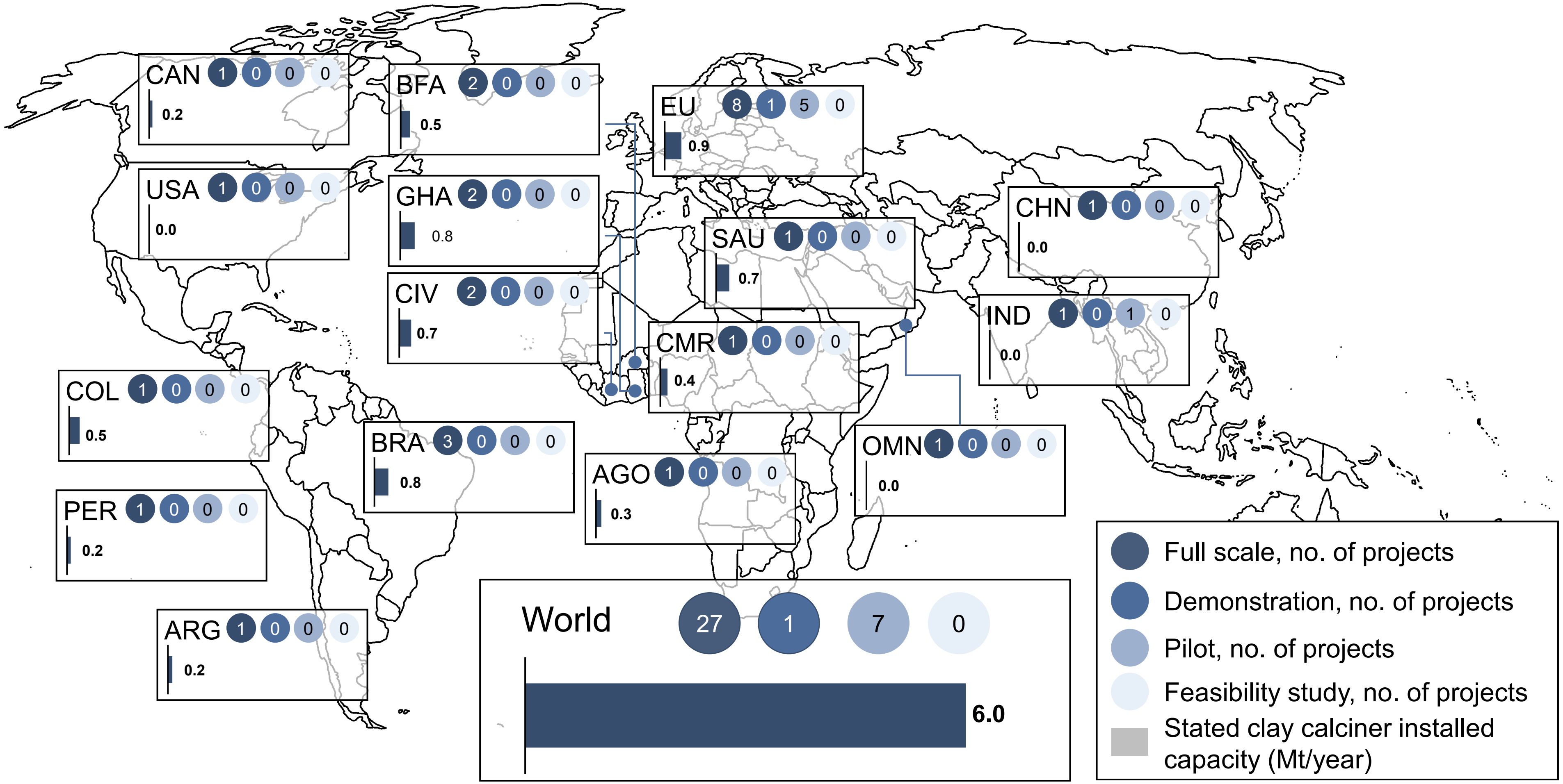
[1] In some countries, SCM substitution occurs during concrete manufacturing rather than cement manufacturing.

Sources: IFC, Strengthening Sustainability in the Cement Industry (2025); IEA, Cement (2023); Congressional Research Service, Cement (2023); IEA, Net Zero by 2050 (2021); RMI, Unleashing the Potential of LC3 (2023); International Cement Review, SCMs: Environmental and Qualitative Benefits (2022).

Credit: Adele Teh, Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Hyae Ryung Kim, and Gernot Wagner.

Announced global cement clay calciner projects expected to reach 380 Mt per year at full capacity; Ghana leads with ~99% share

Global distribution of stated clay calciner installed capacity, project count and Mt/year, Dec. 2024



Observations

- Savings in cement and binders, including calcined clays, accounts for **11% of planned emissions reductions** in the GCCA 2050 net-zero roadmap, which has been backed by 40 cement producers since 2021.
- **Africa** accounts for **44%** of stated capacity from announced clay calciner projects.
- Clay calcination kilns are **less capital intensive** and easily integrated into existing cement plants — an attractive option for developing nations with limited industrial investment capacity.
- Many developing countries have **abundant clay reserves** but rely on imported clinker due to scarce high-grade limestone.
- Clay-based alternatives offer a **cost-effective solution** to meet rising cement demand amid rapid urbanization in developing countries.

Source: GCCA and LeadIT, Green Cement Technology Tracker (2024).
Credit: Adele Teh, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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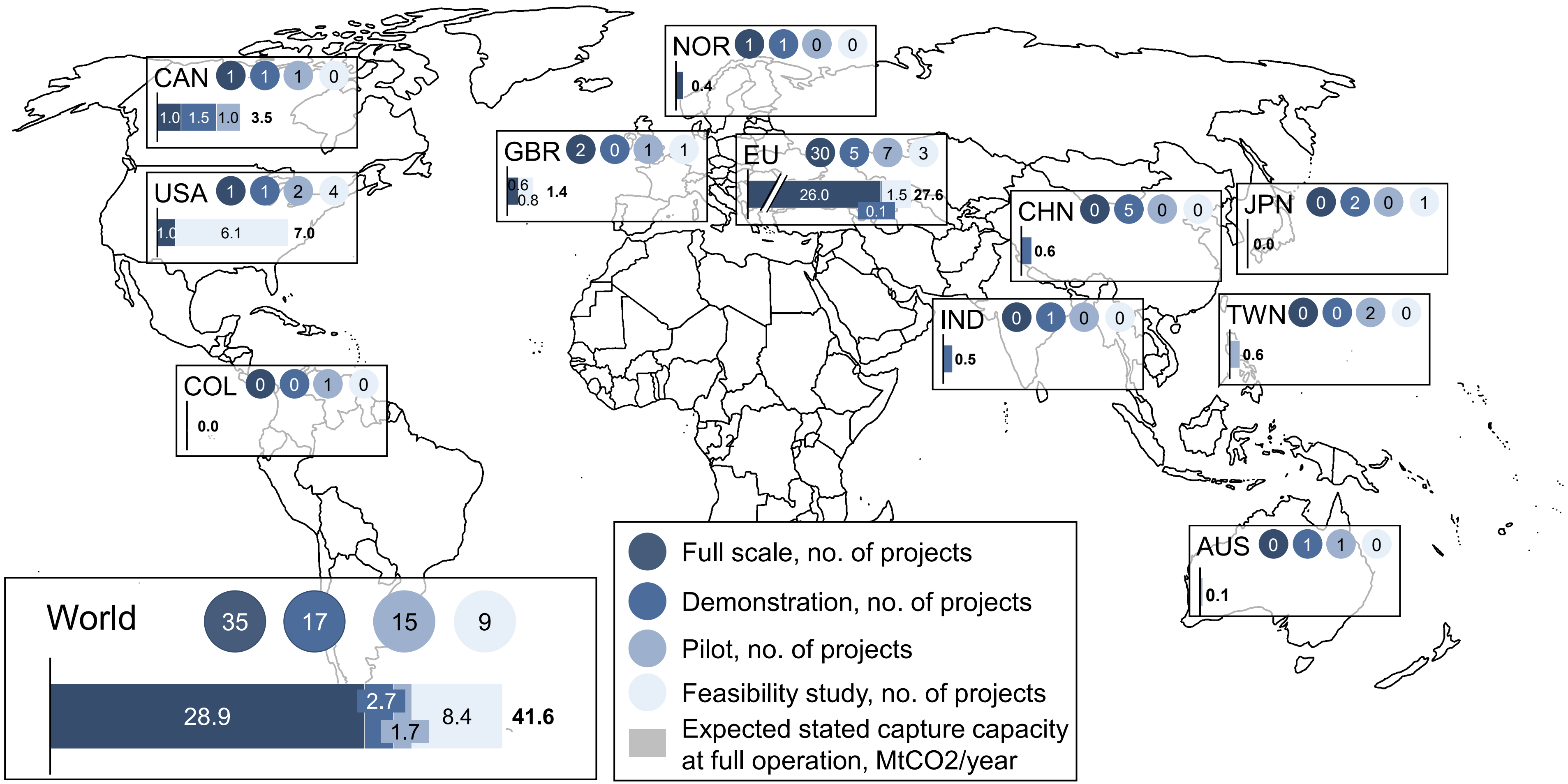
Announced global cement CCUS projects >40 $MtCO_2$ per year at full capacity; EU leads with ~66% share

Global distribution of stated carbon capture capacity, project count and MtCO2/year, Dec. 2024



Observations

- CCUS accounts for **36% of planned emissions reductions** in the GCCA 2050 net-zero roadmap, which has been backed by 40 cement producers since 2021.
- The roadmap targets **1,370 Mt of CO_2** captured by 2050.
- **North America and the EU** account for **92%** of stated capacity from announced cement CCUS projects.
- **High capital needs** and **strong policy support** (e.g., U.S. 45Q tax credit) drive CCUS deployment in developed countries.
- **Existing oil and gas infrastructure** in developed markets (e.g., pipelines, storage facilities, geological data) enables faster rollout.
- For example, Norway's Northern Lights project utilizes existing North Sea oil infrastructure to store CO_2.

Source: GCCA and LeadIT, Green Cement Technology Tracker (2024).
Credit: Adele Teh, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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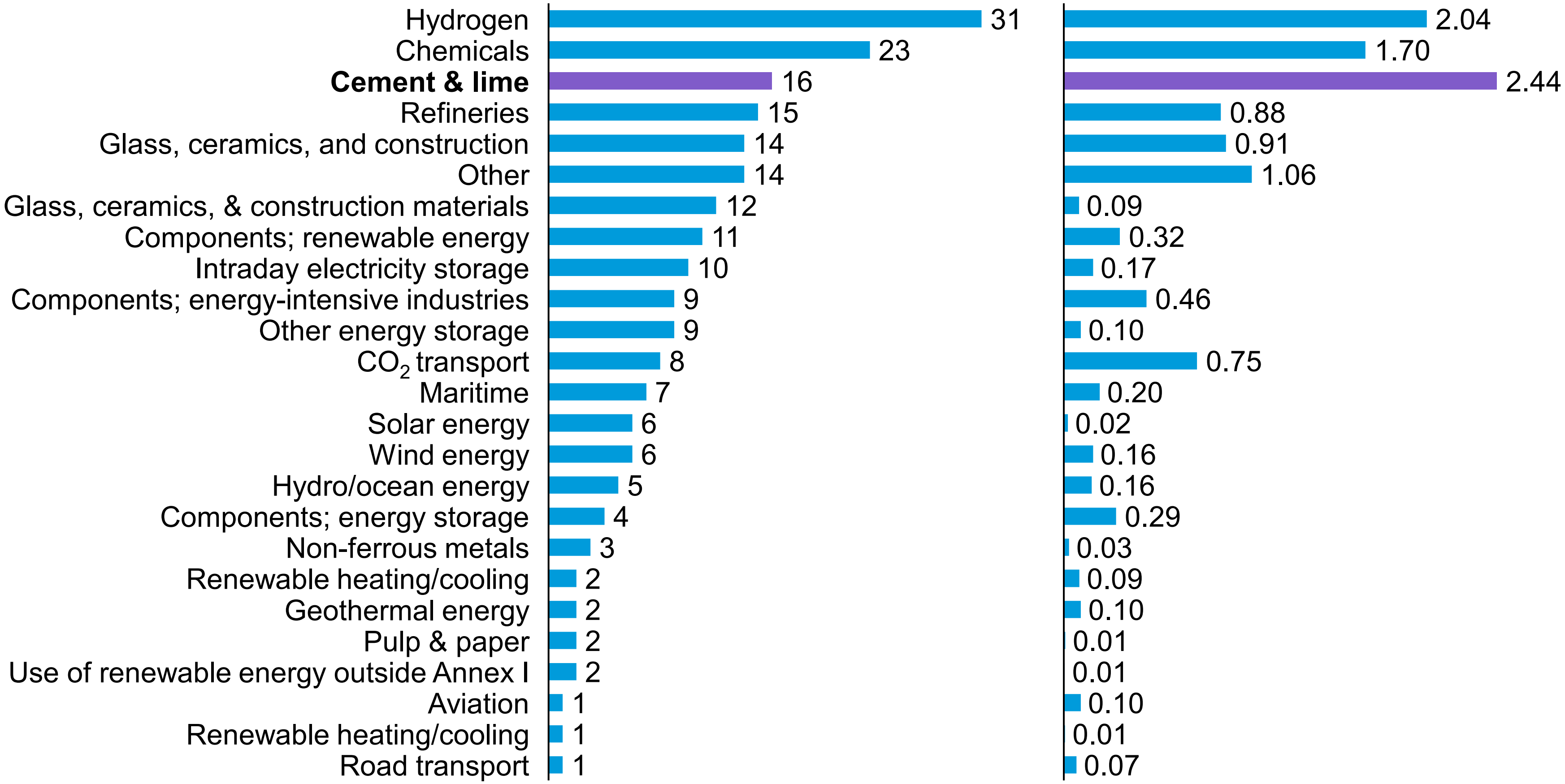
The EU Innovation Fund has invested in 16 cement projects for demonstration of innovative low-carbon technologies

Number of projects EU Innovation Fund has invested in, 2025 | **EU contribution by sector in 2025, billions EUR**



Observations

- In the EU, polluters have to pay for their greenhouse gas emissions via the **Emissions Trading System** (ETS).
- The money raised via the EU ETS is **reinvested into the Innovation Fund**, one of the world's largest funding programs for the demonstration of innovative low-carbon technologies.
- As of September 2025, **16** out of **214** projects funded by the EU Innovation Fund (US$12.2 billion) are cement-related projects, totaling **US$2.44 billion** in investment.
- Though all cement projects have different technology installations, they **all have CCUS installation plans** as part of the projects.

Source: EU Innovation Fund, Innovation Fund Portfolio (2024).
Credit: Hoshi Ogawa, Ariela Farchi, Sho Tatsuno, Jessica Cong, Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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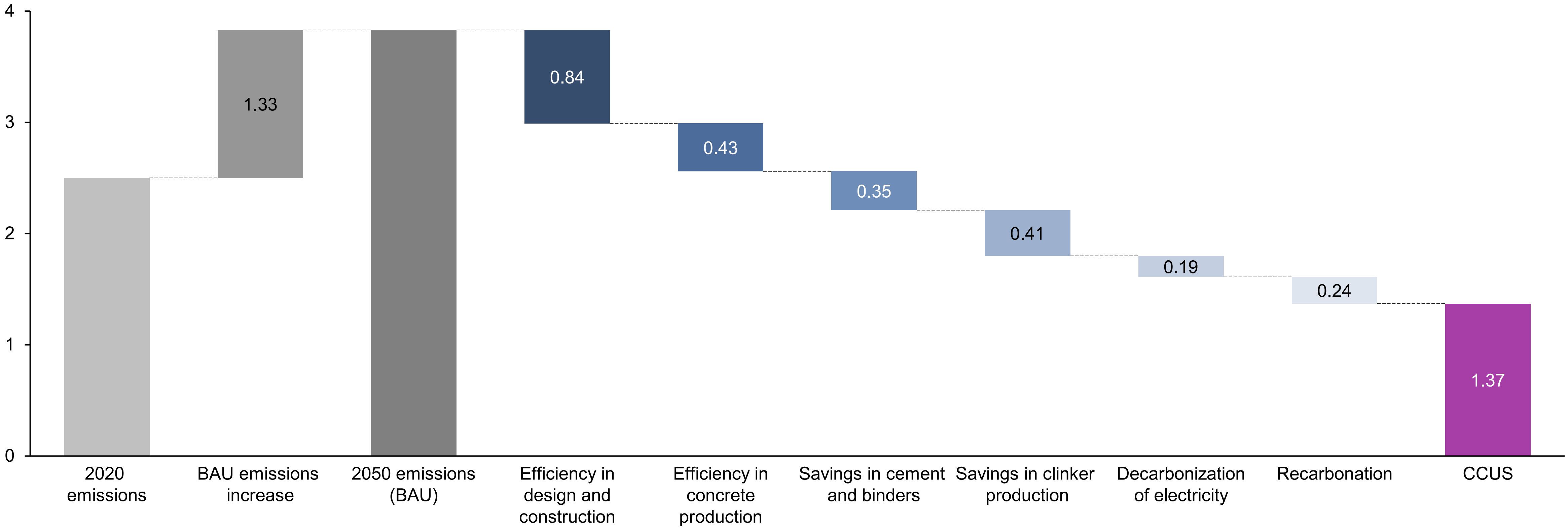
GCCA's net-zero roadmap cites CCUS and improved material efficiency as the key levers for decarbonizing the cement sector

GCCA roadmap: Cement decarbonization levers by 2050

Cement industry emissions, *2020-2050, $GtCO_2$*



Source: GCCA, Concrete future, roadmap to net zero (2021).
Credit: Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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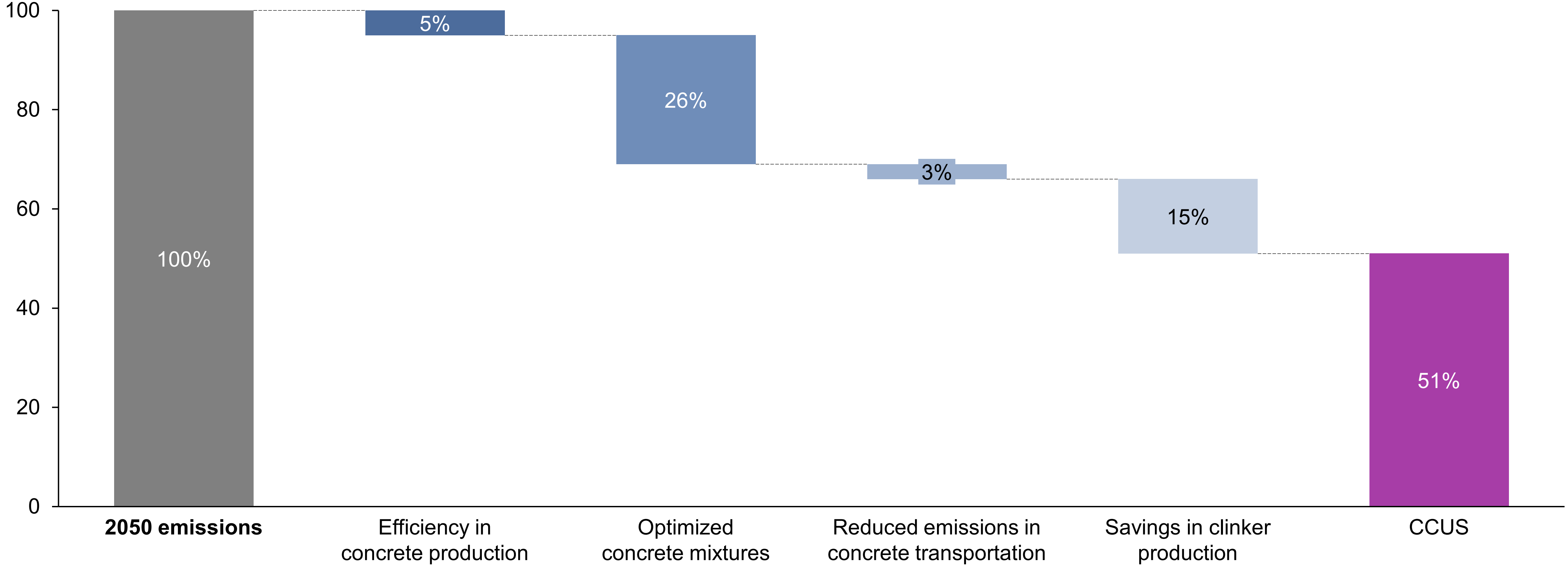
ACA pathway expects CCUS and concrete mixture optimization to lead decarbonization, abating ~51% and ~26%, respectively

PCA carbon-neutrality levers, 2050

Percentage share of CO_2 emissions abated by measures



Source: American Cement Association, Roadmap to Carbon Neutrality (2024).
Credit: Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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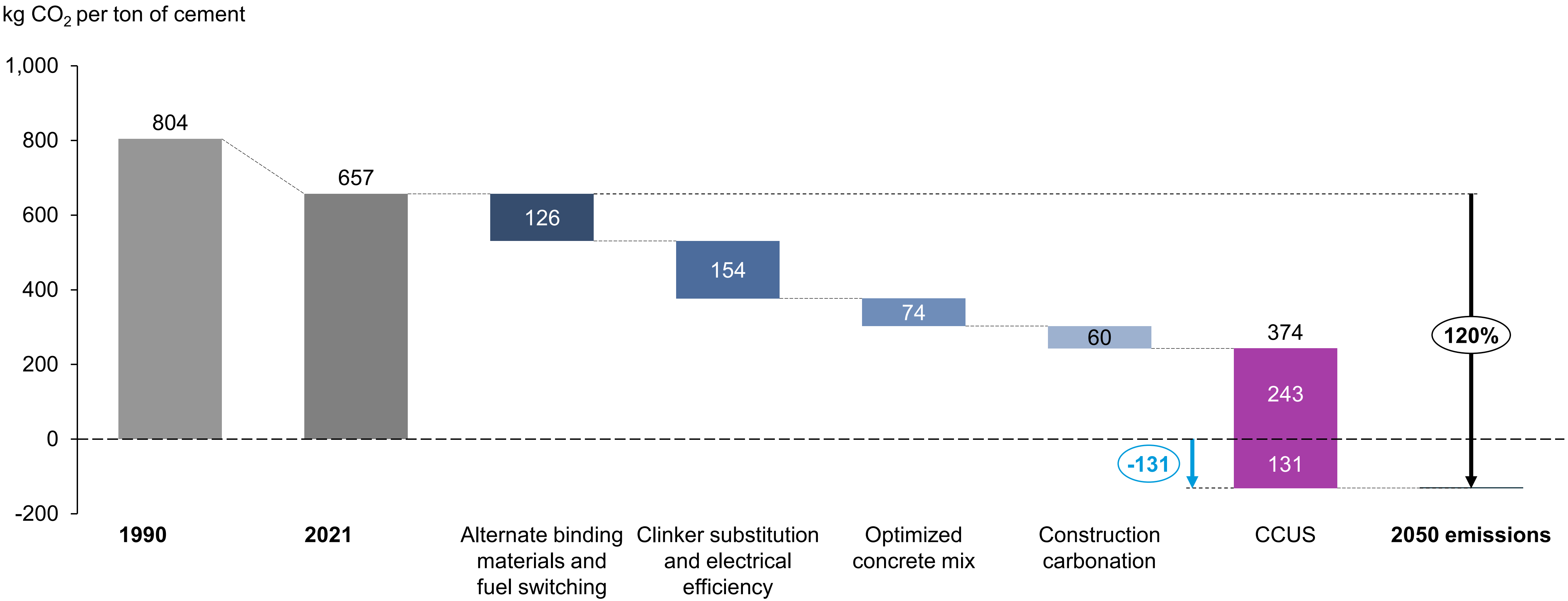
CEMBUREAU's 2050 roadmap projects -131 kgCO_2/t cement emissions through CCUS, clinker substitution, and circularity

CEMBUREAU total process emissions, including downstream, 1990-2050



Sources: CEMBUREAU, From Ambition to Deployment (2024).
Credit: Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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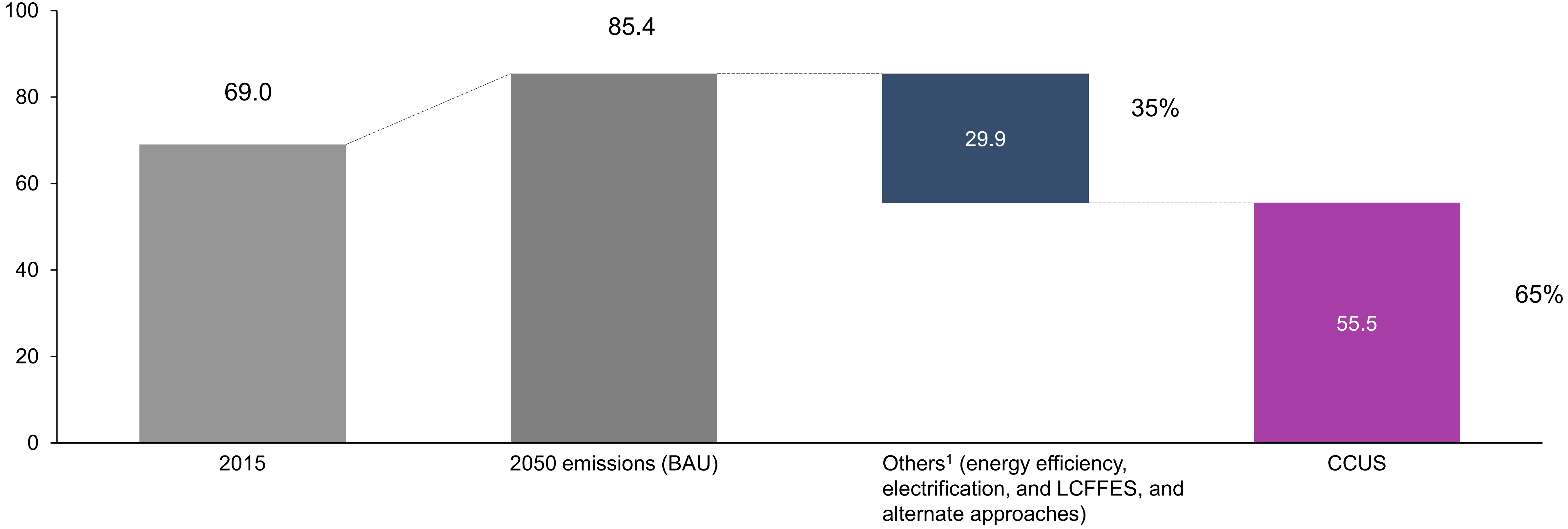
DOE's Industrial Decarbonization Roadmap highlights CCUS as a key lever reducing 65% of CO_2 emissions for the U.S. market

DOE Industrial Decarbonization Roadmap emissions for U.S. cement manufacturing sector, 2015-50, $MtCO_2$



[1] Percent share of emissions abated by energy efficiency, electrification, and LCFFES, and alternate approaches.
Source: DOE, Industrial Decarbonization Roadmap (2022).
Credit: Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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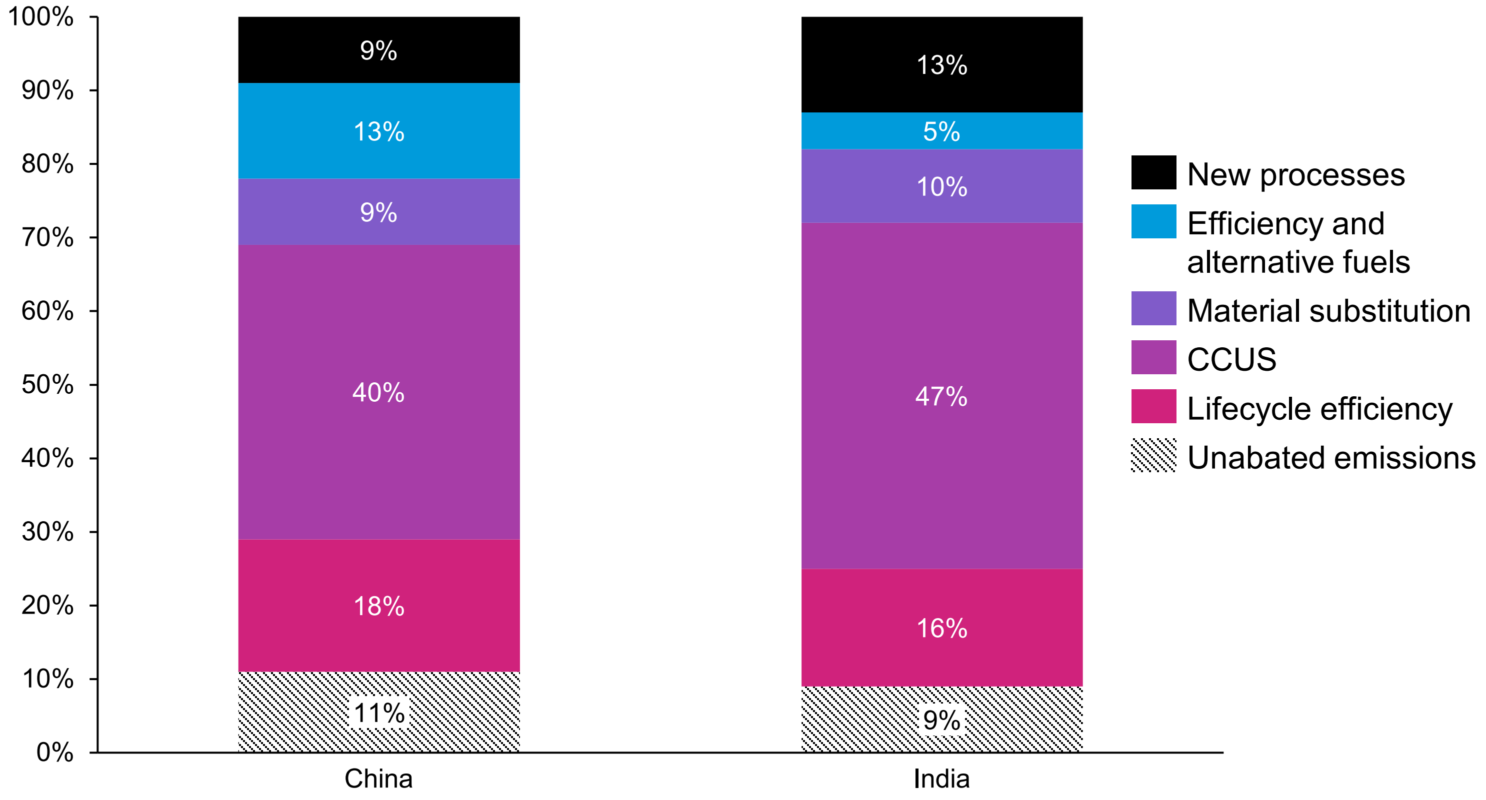
Emerging cement producing economies, China and India consider new processes alongside traditional decarbonization levers

Share of CO_2 emissions abated by key decarbonization levers by 2050

ClimateWorks projections



Observations

- **CCUS dominates:** The largest share of emissions abatement comes from CCUS in both countries — **India (47%)**, **China (40%)** — signaling reliance on large-scale capture infrastructure.
- **India bets on innovation:** Greater share in new processes (13% vs. 9% China) shows focus on tech upgrades.
- **Low impact from efficiency:** Efficiency and alternative fuels remain limited (9% to 10%) in both pathways.

Source: ClimateWorks Foundation, Insights (2021).
Credit: Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner. Share with attribution: Wagner et al., “Decarbonizing Cement” (16 July 2026).

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Glossary

BAU	Business as usual
$CaCO_3$	Calcium carbonate
CaO	Calcium oxide
CapEx	Capital expenditure(s)
CBAM	Carbon Border Adjustment Mechanism
CCUS	Carbon capture, utilization, and storage
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	CO_2 equivalent, using global warming potential as conversion factor
EBITDA	Earnings before interest, taxes, depreciation, and amortization
ETS	Emissions Trading System
EPD	Environmental Product Declarations
EU	European Union
FMC	Federal Materials Council
GCCA	Global Cement and Concrete Association
GPP	Green public procurement
RDF	Refuse-derived fuel
GSA	General Services Administration
Gt	Gigaton (billion metric tons)
GWP	Global warming potential
H_2	Hydrogen
H_2O	Water
IDDI	Industrial Deep Decarbonization Initiative
IEA	International Energy Agency
IRA	Inflation Reduction Act
LCA	Lifecycle assessment
Mt	Megaton (million metric tons)
MTPA	Million tons per annum
NZE	Net-zero emissions
O_2	Oxygen
OpEx	Operational expenditure(s)
PCA	Portland Cement Association
RMC	Ready-mix concrete
SCM	Supplementary cementitious materials
SRF	Solid recovered fuel