Columbia Business School
Climate Knowledge Initiative

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Decarbonizing Cement

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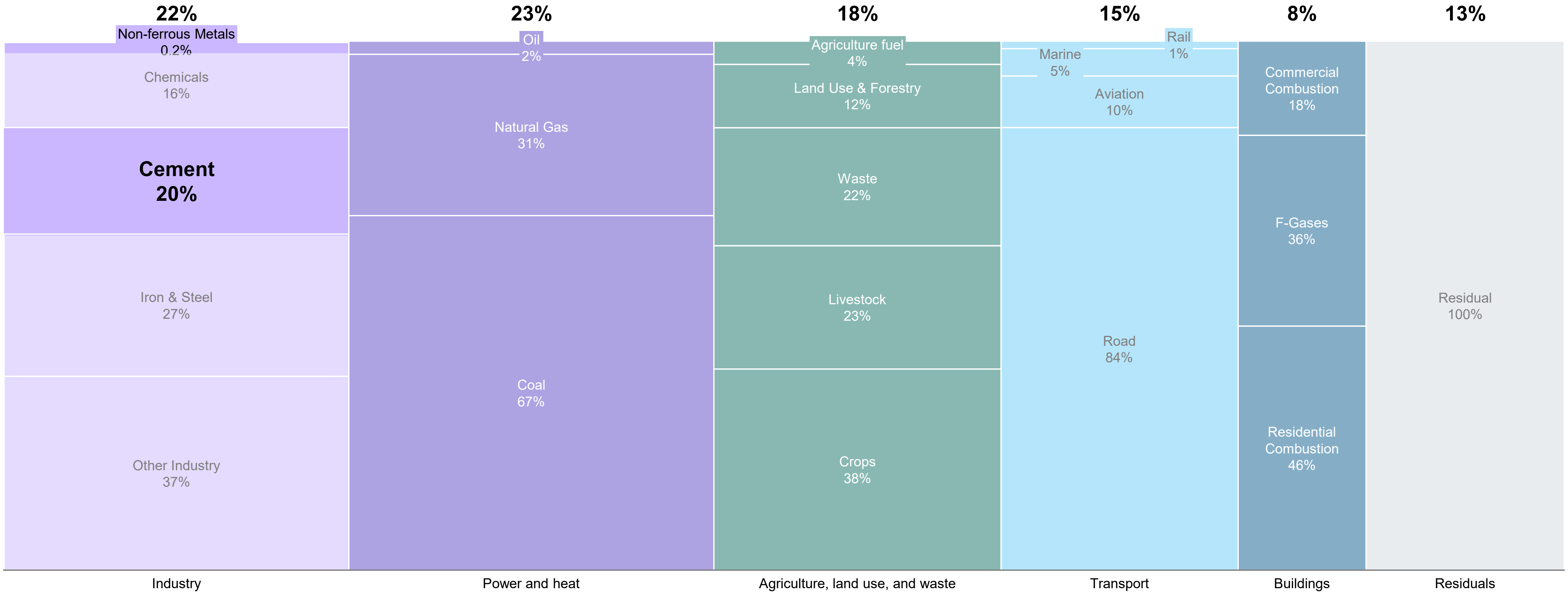
Cite as: Wagner *et al*. “Decarbonizing Cement,” Columbia Business School Climate Knowledge Initiative (16 July 2026).

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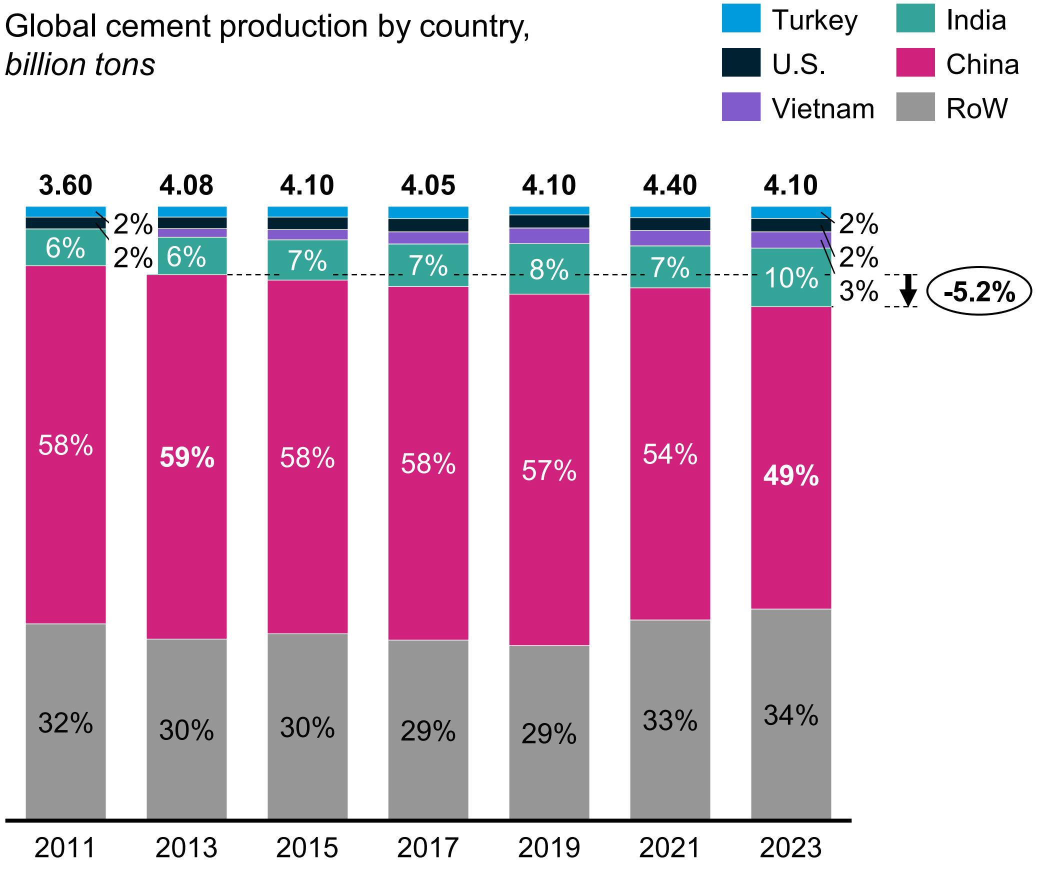
China has dominated cement production for the past decade, but share expected to decline while emerging markets' demand grows

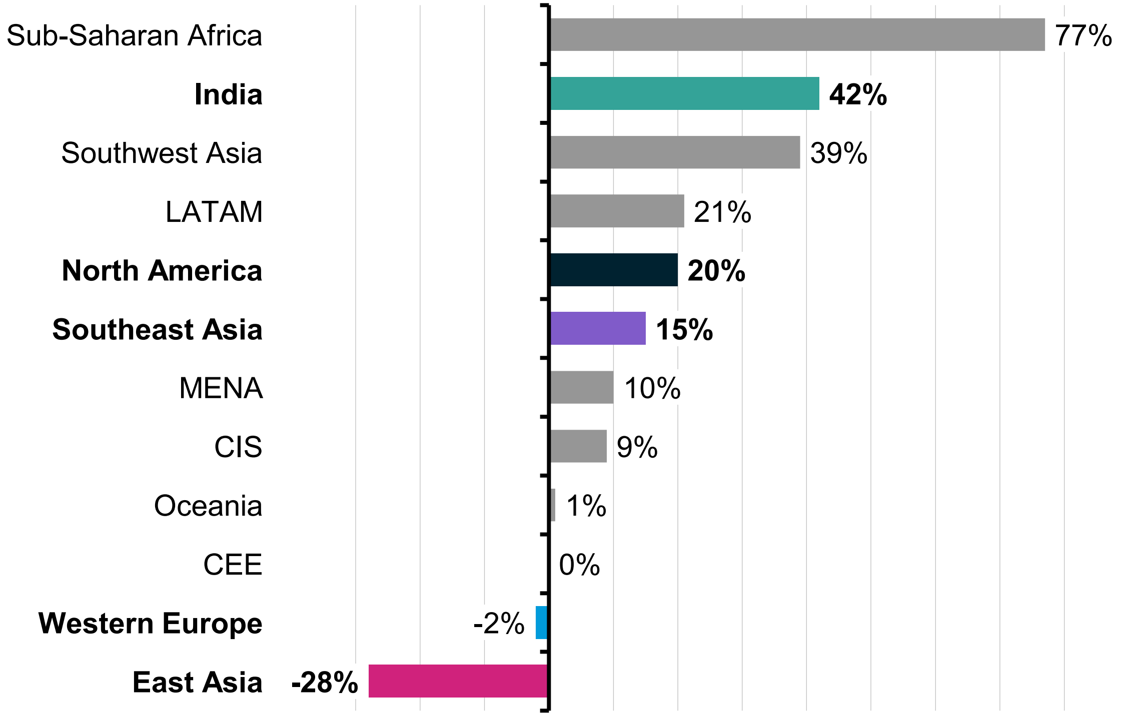
China's production share peaked in 2013, then dipped below 50% of global in 2023 for the first time in 15 years

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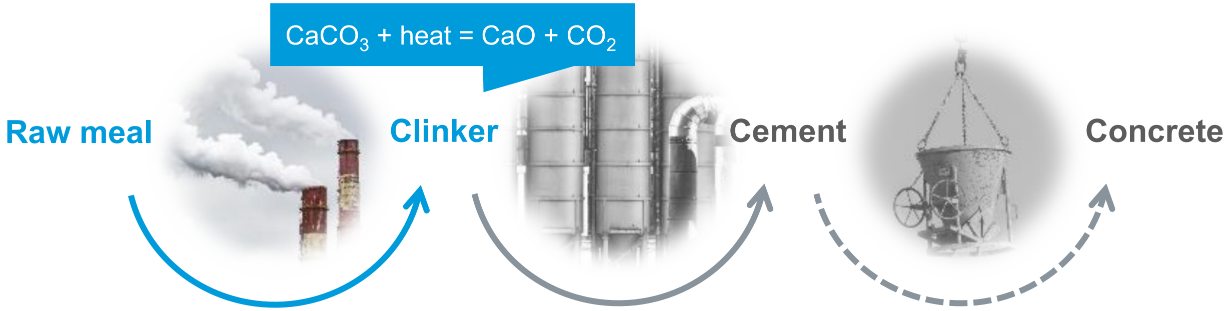
Clinker production is ~85% of cement emissions; dry-kiln adoption has led to significant efficiency gains

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

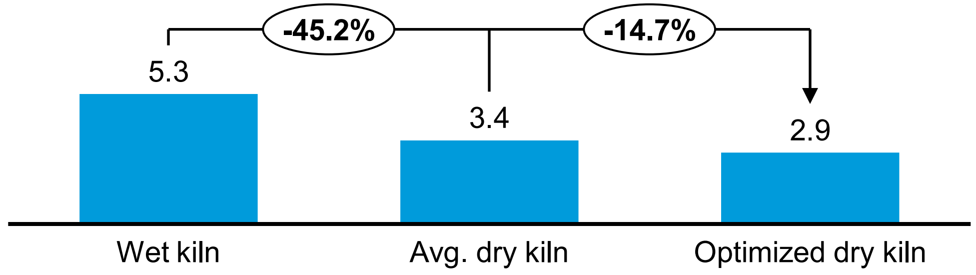
- Limestone is partially decomposed into lime in a combustion chamber before entering the kiln.

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.

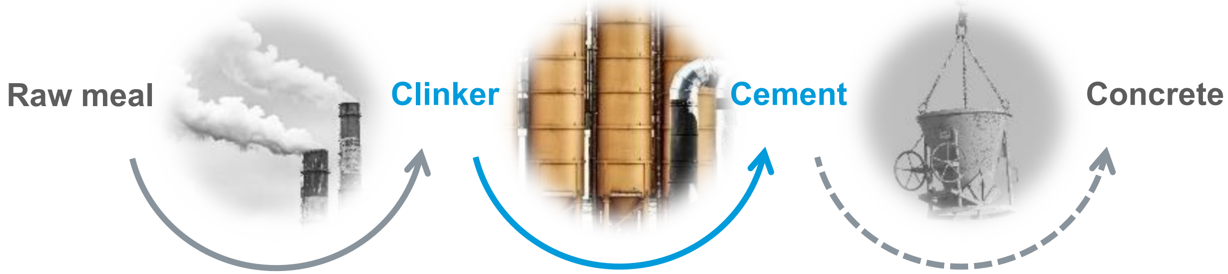
[1] The production process shown assumes dry-kiln processing, which has widely replaced wet-kiln processing globally.

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).

Credit: Nicolas Herrera Isaza, Jessica Cong, 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]



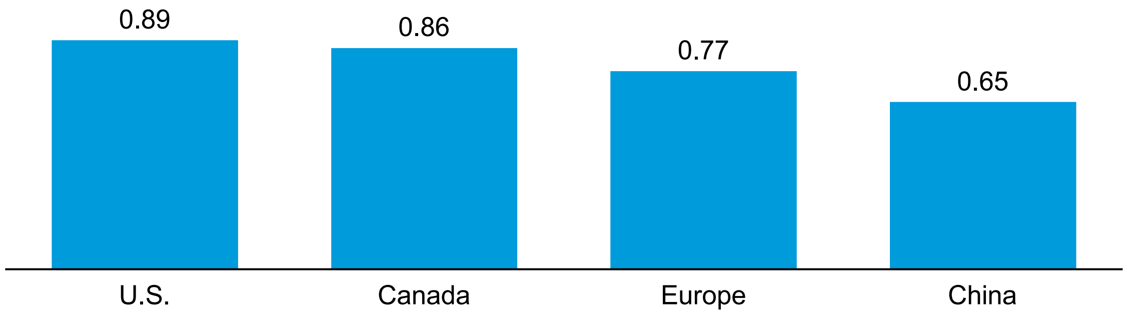
1 Cooling

- 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.

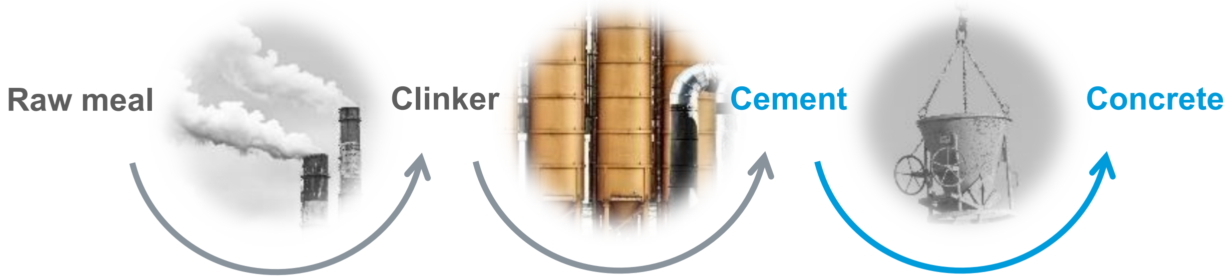
[1] The production process shown assumes dry-kiln processing, which has widely replaced wet-kiln processing globally.

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.

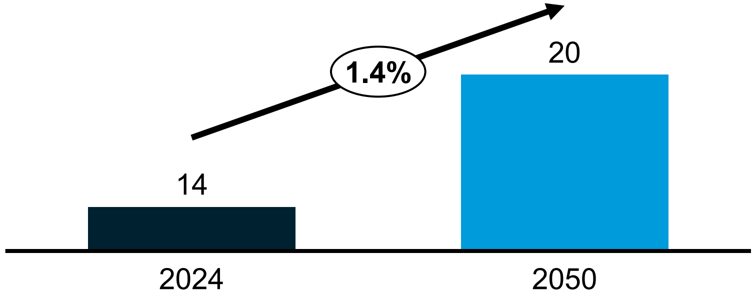
2 Add aggregates

- 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).

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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, $/t$CO_2$e	-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)

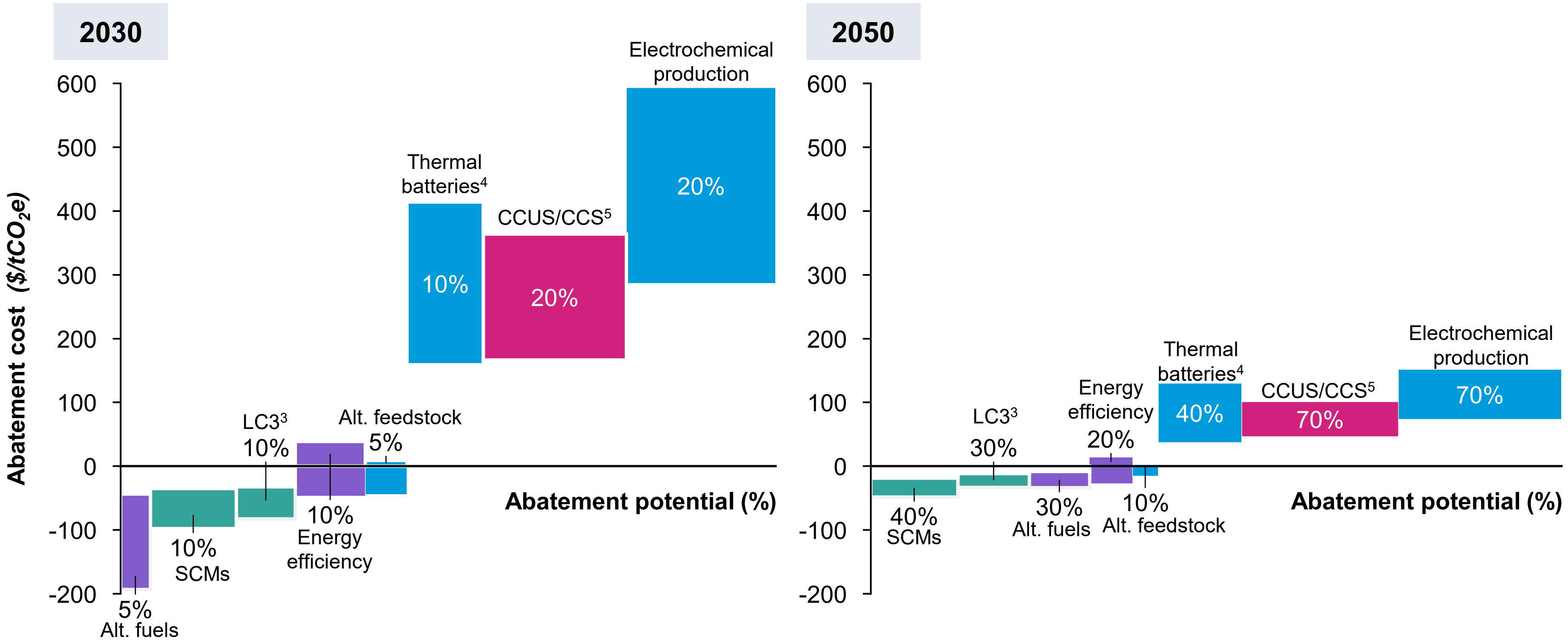
[1]Unconstrained theoretical abatement potential for a given ton of cement produced for each approach in isolation. [2]Assumes clean energy source. [3]Abatement cost of emerging technologies is based on estimates and has high uncertainty. [4]Reflects the approximate emissions gap after other measures, 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.**

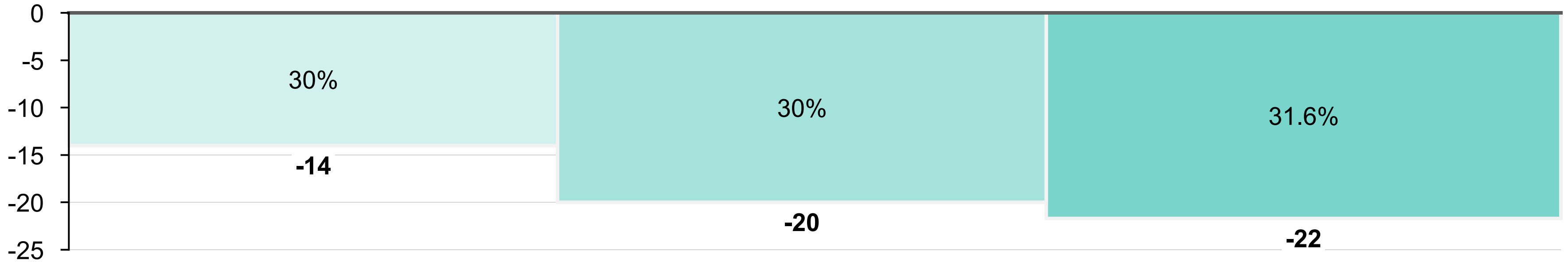
[1]Abatement cost of emerging technologies is based on estimates and has high uncertainty. [2]Abatement potential is calculated as unconstrained and theoretical for each approach in isolation. [3]Despite TRL 9, market penetration of LC3 remains low due to slow standards adoption, limited supply chain 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).

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_2e$) 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).

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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.

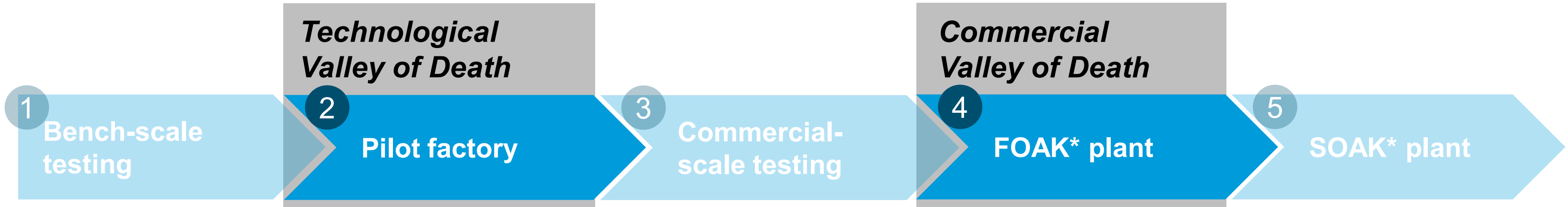
[1]FOAK = first of a kind; SOAK = second of a kind. [2]Capital costs refer to construction CapEx only; excludes OpEx, financing costs, and pre-FID development expenditure.

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



Technological Valley of Death

- **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

- **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.

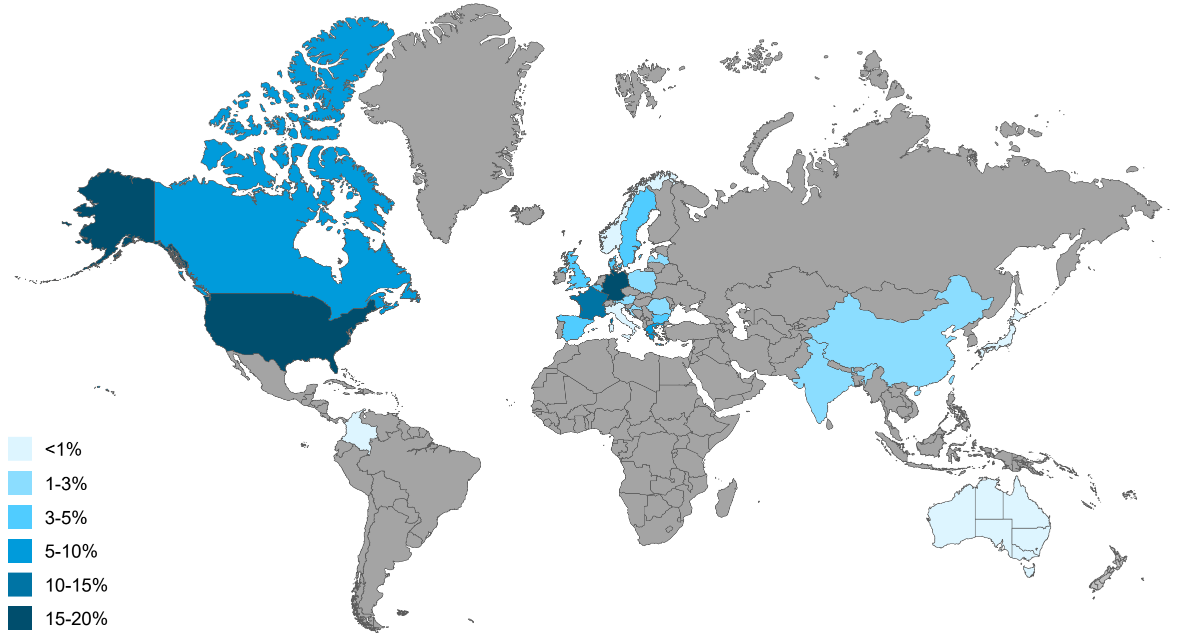
Observations

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

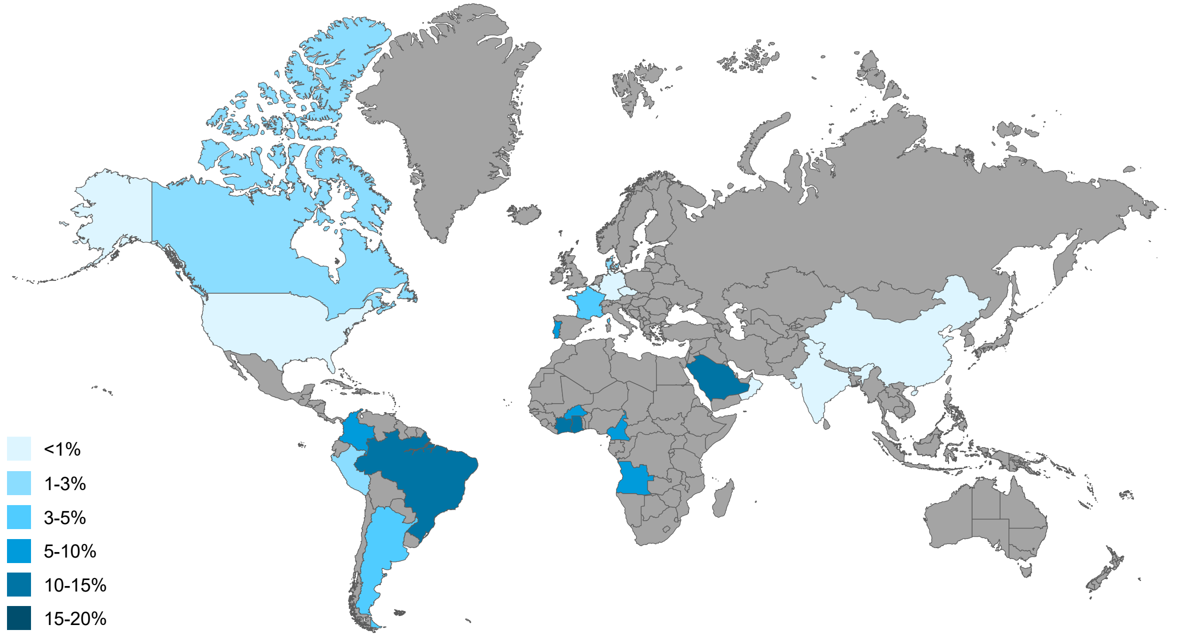
Investment capacity and infrastructure drive CCUS in Global North; clay reserves and capital constraints drive LC3 in South

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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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
Push (Carrots)	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.**
System enablers (Neutral)	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.
Prohibit (Sticks)	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).

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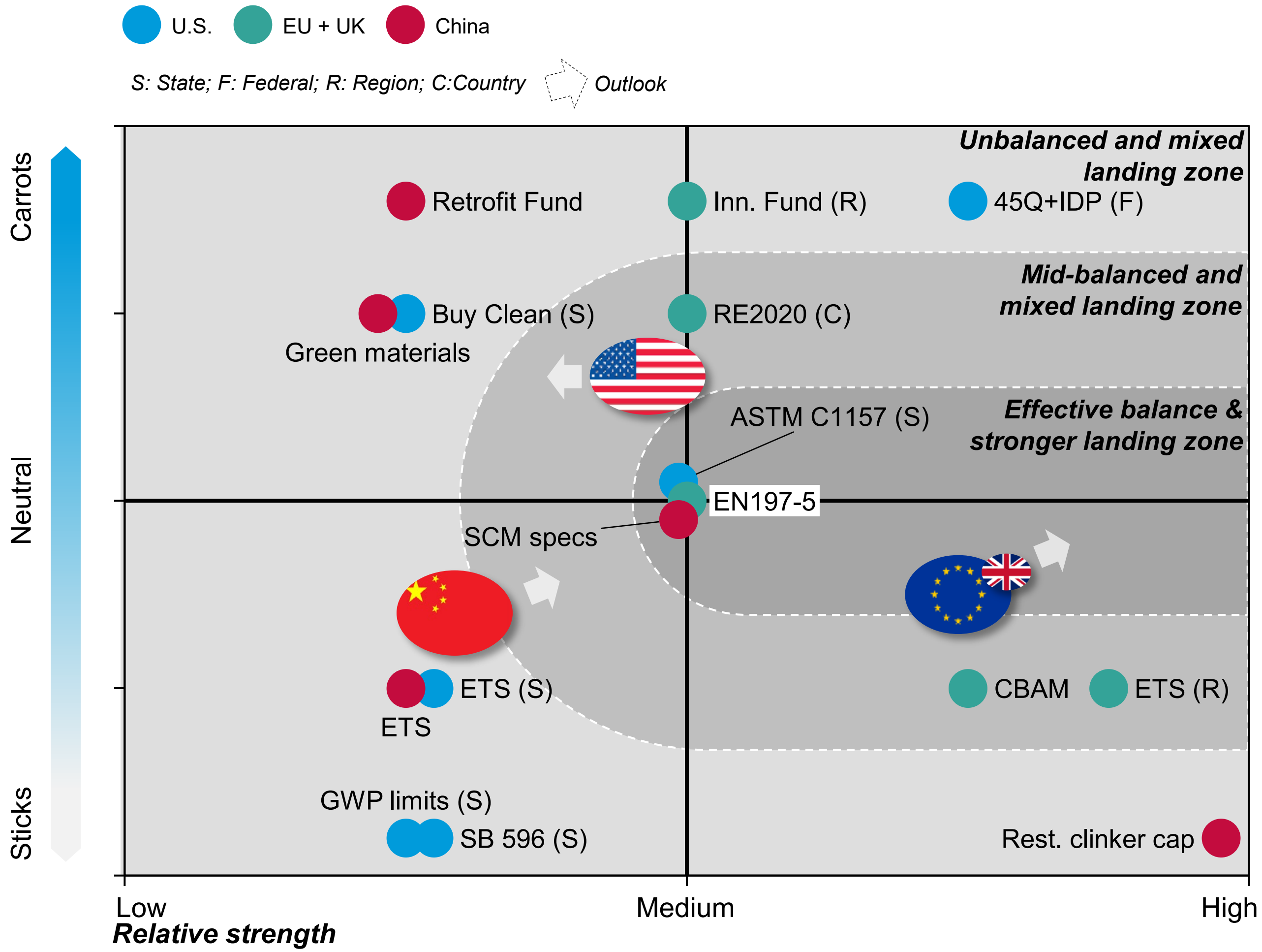
EU + UK and China are tightening restrictive policies; U.S. is pulling back on incentive-based support



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 $85) tCO$_2$e + 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.

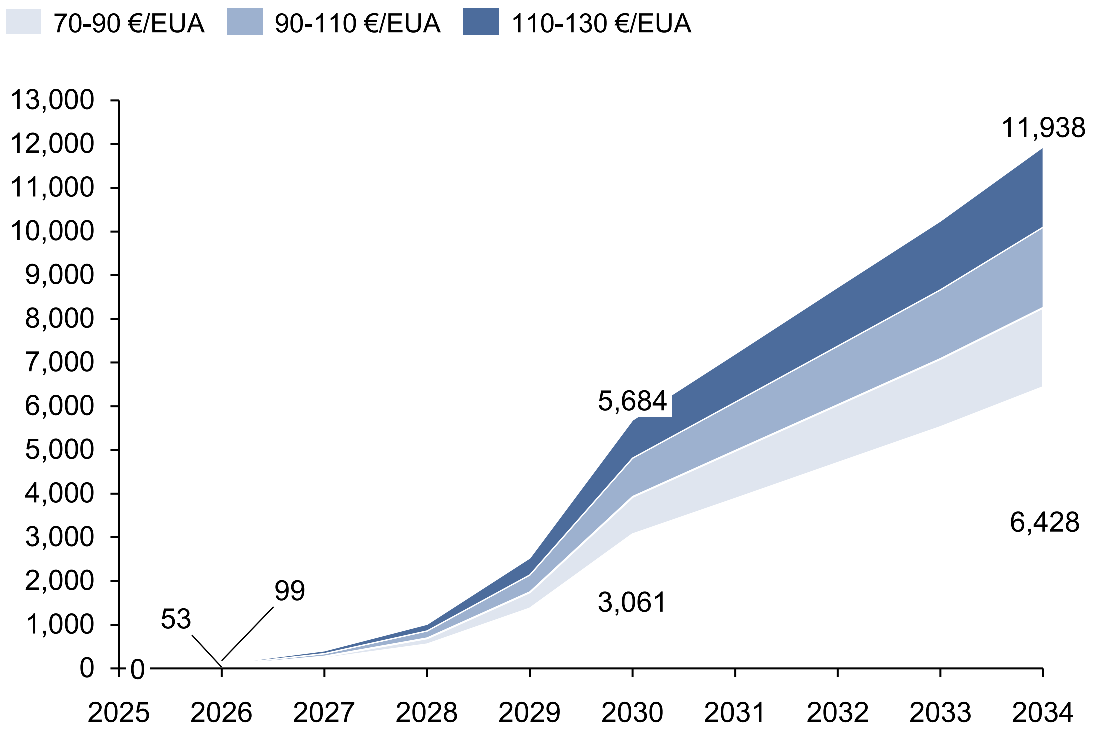
Sources: WEF, Industry NZ tracker (2023); Climate Bond Initiative (2023); EU, Innovation Fund (2024); EU, Net-Zero Industry Act (2024); EU, ETS (2024); ICAP, California ETS (2024); EU, CBAM (2024); GPP Pledge (2023); Office of Sustainability, Federal Buy Clean Initiative (2024); S&P, IRA 45Q (2023); 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).

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

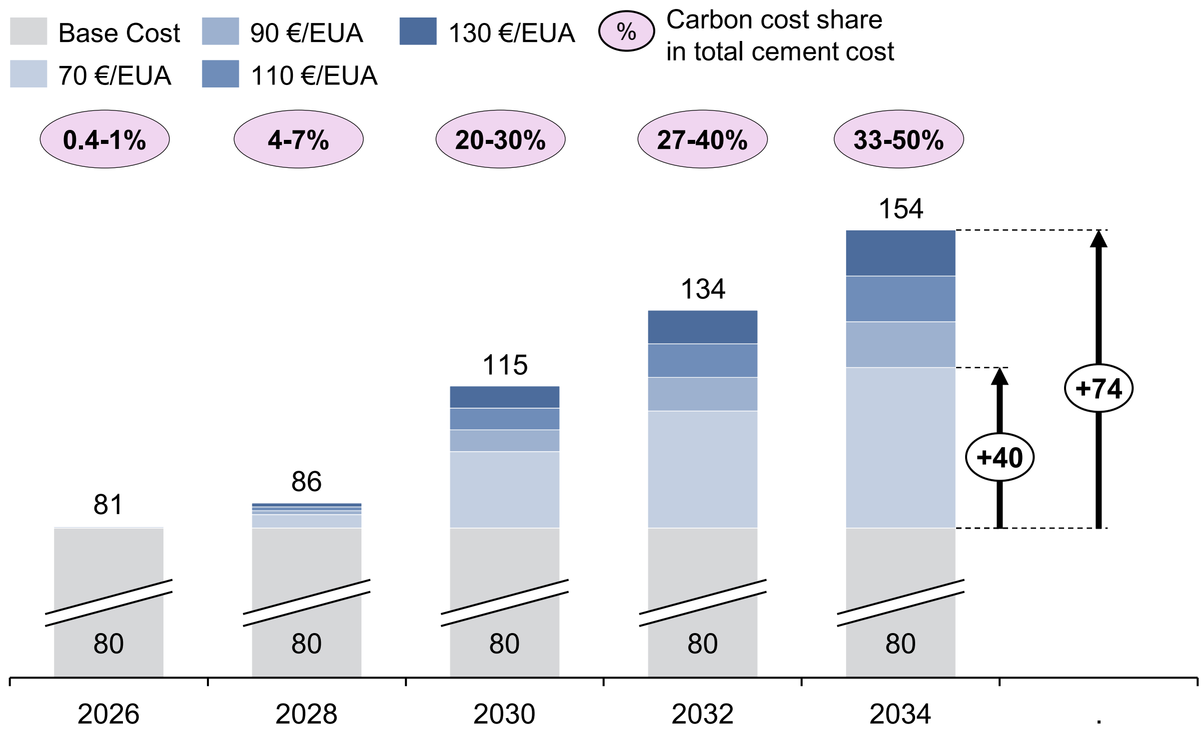
Even in a conservative scenario, total allowance costs to the cement industry will see a sharp increase by 2034

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*

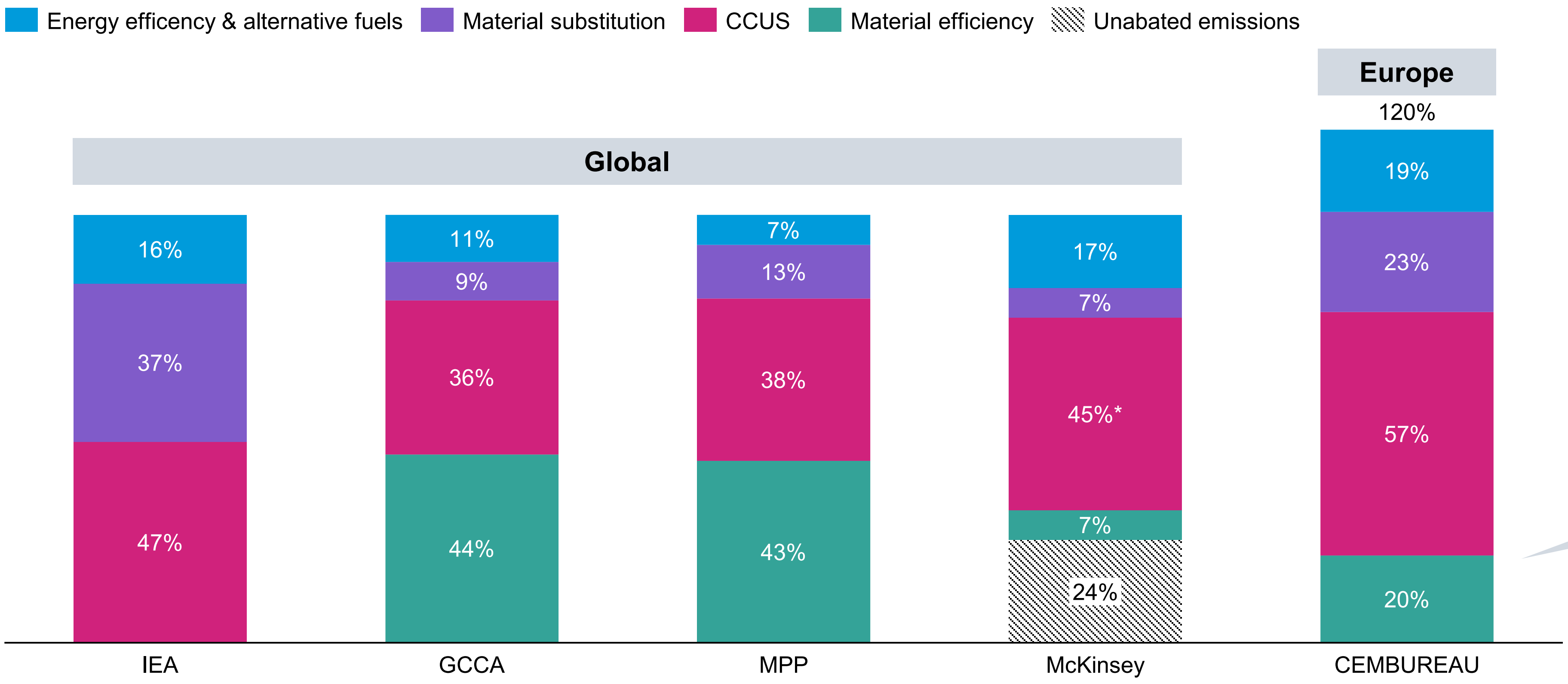


Assumptions: Emissions intensity 0.57 tCO_2e/t cement as benchmark; stable cement consumption (production-exports+imports) at 160 Mt/year
Sources: CKI analysis; BCG, Decoding ETS and CBAM (2025); European Environment Agency, Use of EU ETS revenue (2024).
Credit: Nicolas Herrera Isaza, Isabel Hoyos, and Gernot Wagner. Share with attribution: Wagner et al., "Decarbonizing Cement" (16 July 2026).

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



Total abatement exceeds 100% because the roadmap includes carbon removal strategies (e.g., CCUS, carbonation) that go beyond reducing emissions, enabling net-negative emissions (-131 kg CO_2/t) by 2050.

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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