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17 October 2024

Decarbonizing Cement

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Cement and Concrete Sector Overview: The Problem

Key messages
Cement and concrete sector overview

The global cement sector is **responsible for ~5 to 8% of global CO_2 emissions.**

- Global cement emissions have **more than doubled since 2000** (from 0.7 gigatonnes in 2000 to 1.6 Gt in 2022).
- Without intervention, emissions are expected to **continue growing due to sustained demand**, driven by rising urbanization and infrastructure development in developing countries.

The production of clinker, the primary binding agent in cement, **accounts for 80 to 90% of cement manufacturing emissions:**

- Thermal emissions from combustion of fossil fuels to make clinker (~30 to 40%)
- Process emissions from calcination of limestone to make clinker (~50 to 60%)

Indirect emissions from electricity usage for transport and machinery **account for ~10% of cement manufacturing emissions:**

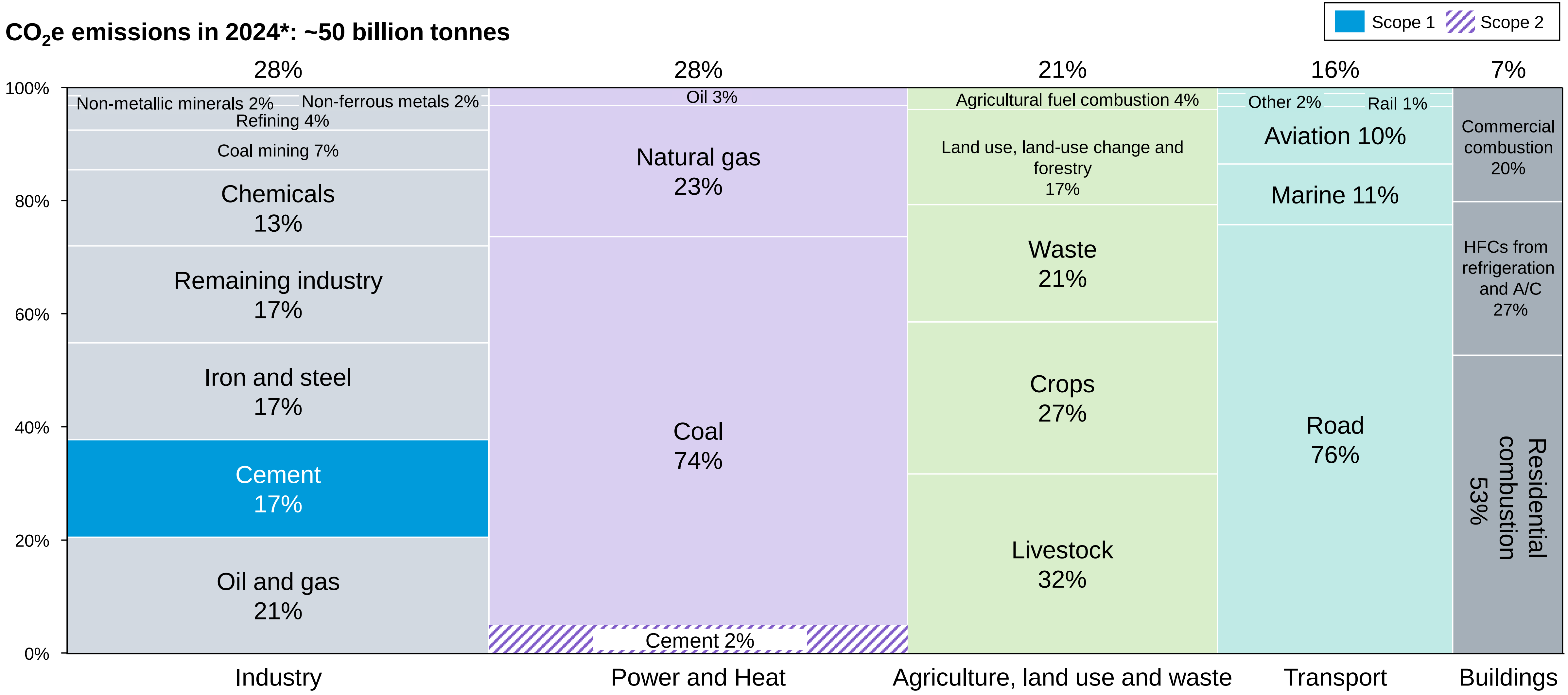
- Energy emissions from cement grinding (~5%)
- Energy emissions from concrete mixing and transportation (~5%)

The **average clinker-to-cement ratio in the US is 0.88** (880 kilograms of clinker per metric tonne of cement) as of 2022.

- The world average clinker-to-cement ratio is 0.76.

Cement sector Scopes 1 and 2 around 5-8% of global CO_2 emissions

CO_2e emissions in 2024*: ~50 billion tonnes



Sources: Scope 1 emissions from Rhodium Group ClimateDeck (September 2024); Scope 2 cement emissions estimated assuming indirect emissions from electricity are 10% of total emissions, IEA (2023);
* 2024 emissions based on projections.
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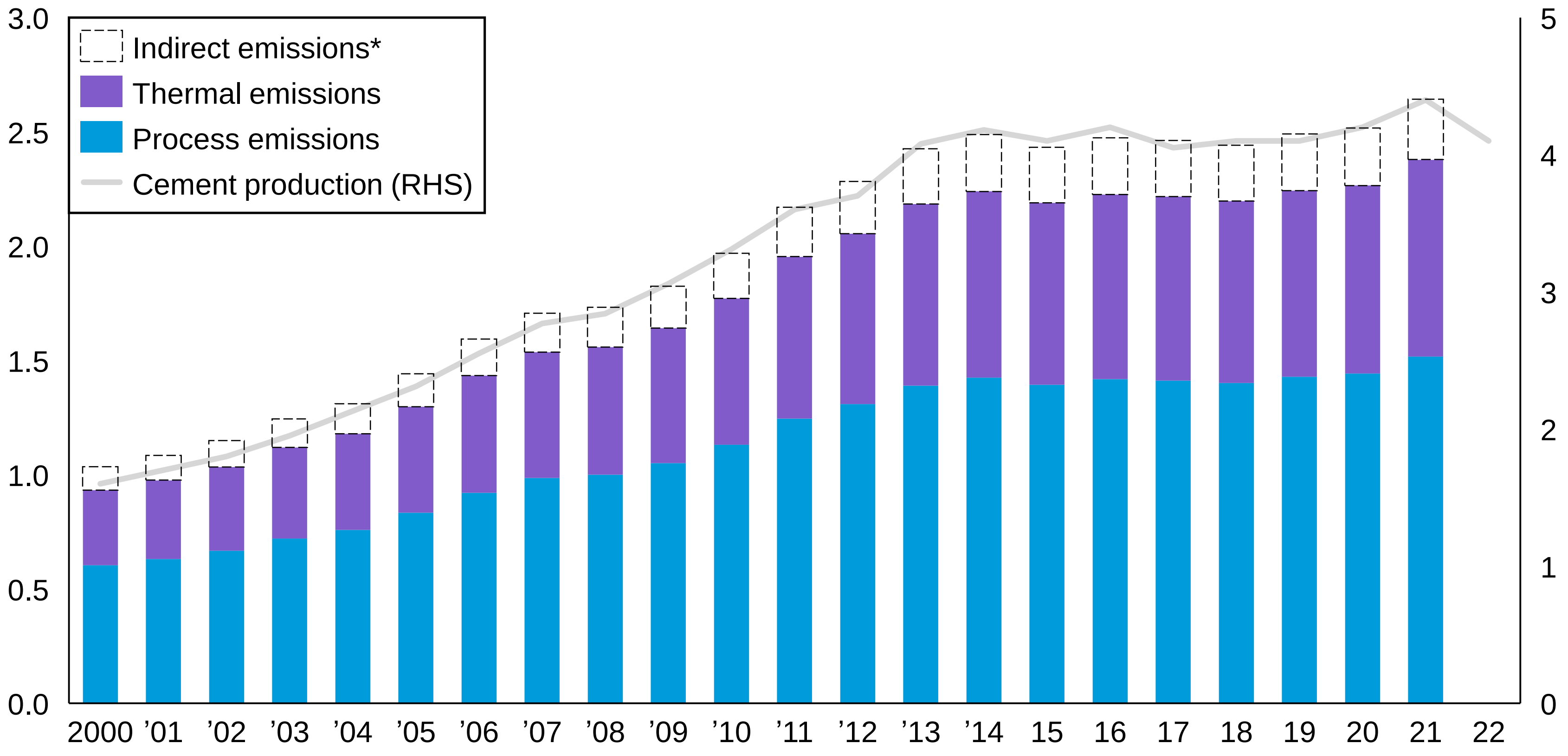
Global cement emissions more than doubled since 2000, in line with cement production

Global CO_2e emissions from cement production, 2000-21
Gt

Global cement production, 2000-22
Gt



Observations

- In recent years, the cement industry has made efforts to **reduce its carbon footprint** by implementing more **energy-efficient processes and technologies**.
- **Gradual conversion from wet-process to dry-process** clinker manufacturing has led to reduced energy consumption.
- Global cement **production capacity increased by 30% in the past decade** and is expected to grow by 14% from 2020 to 2030 and another 22% by 2050.
- **China,** the largest cement producer (accounting for over 50% of global production), saw a **4.5% decline in cement output** in 2023, to the lowest level since 2010.
- The slowdown in China is **expected to be offset by production increases** in Southeast Asia, Latin America, and Africa to meet their long-term demand and development needs.

* Estimated assuming indirect emissions from electricity account for 10% of total emissions from cement production.
Sources: Rhodium Group ClimateDeck (September 2023), IEA (2023), Fitch Ratings (2024)
Credit: Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

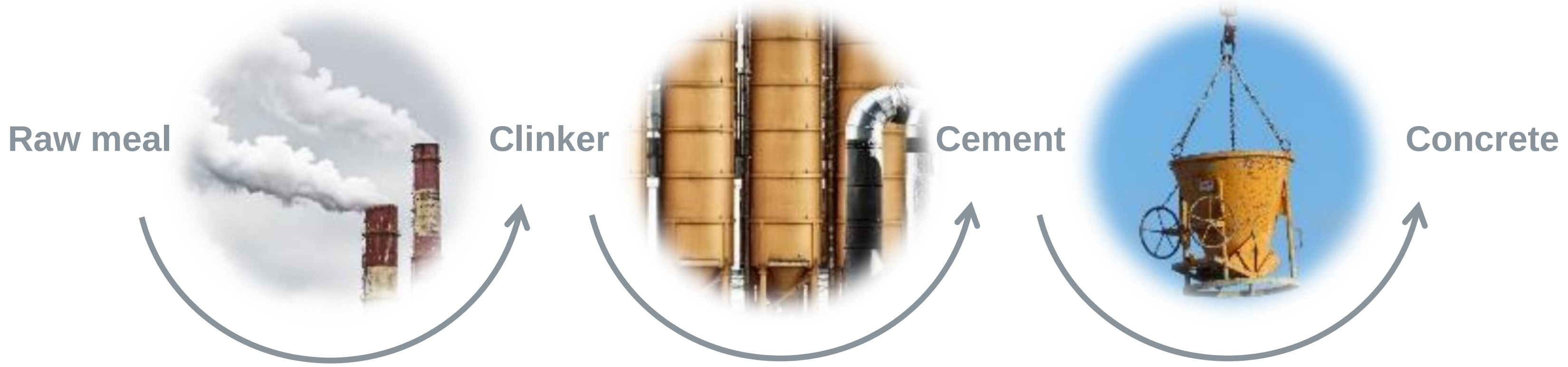
Clinker production accounts for over 80% of cement emissions

1. **50 to 60% of emissions come from the calcination process** that extracts lime (CaO) from limestone ($CaCO_3$) in a chemical reaction that produces CO_2 as a byproduct.

2. **30 to 40% of emissions** come from the fuels used to generate high heat at the kiln, where the calcination process takes place.

Limestone calcination accounts for ~50 to 60% and fossil fuel combustion for ~30 to 40% of cement emissions

Cement/concrete production process



	Calcination of limestone	Fuel combustion for kiln	Non-clinker related emissions
Description	The calcination process that extracts lime (CaO) from limestone ($CaCO_3$) is a chemical reaction that produces CO_2 as a byproduct.	Emissions from the combustion of fuels used to heat the kiln where the calcination process takes place up to 1,450°C.	Emissions associated with powering the mill that crushes raw materials, the clinker cooler, cement mill, and the transportation of materials
% of cement emissions	 ~50-60%	 ~30-40%	 ~10%
CO_2 emissions	479 kg/tonne	319 kg/tonne	127 kg/tonne
Energy intensity	4.25 GJ/tonne	3,150 MJ/tonne	745 MJ/tonne

Note: *The production process shown assumes dry-kiln processing, which has widely replaced wet-kiln processing globally.
Sources: Portland Cement Association (2024), CEMBUREAU (2021), McKinsey (2020), Department of Energy Liftoff Report (2023); IEA (2023); EuLA (2019)
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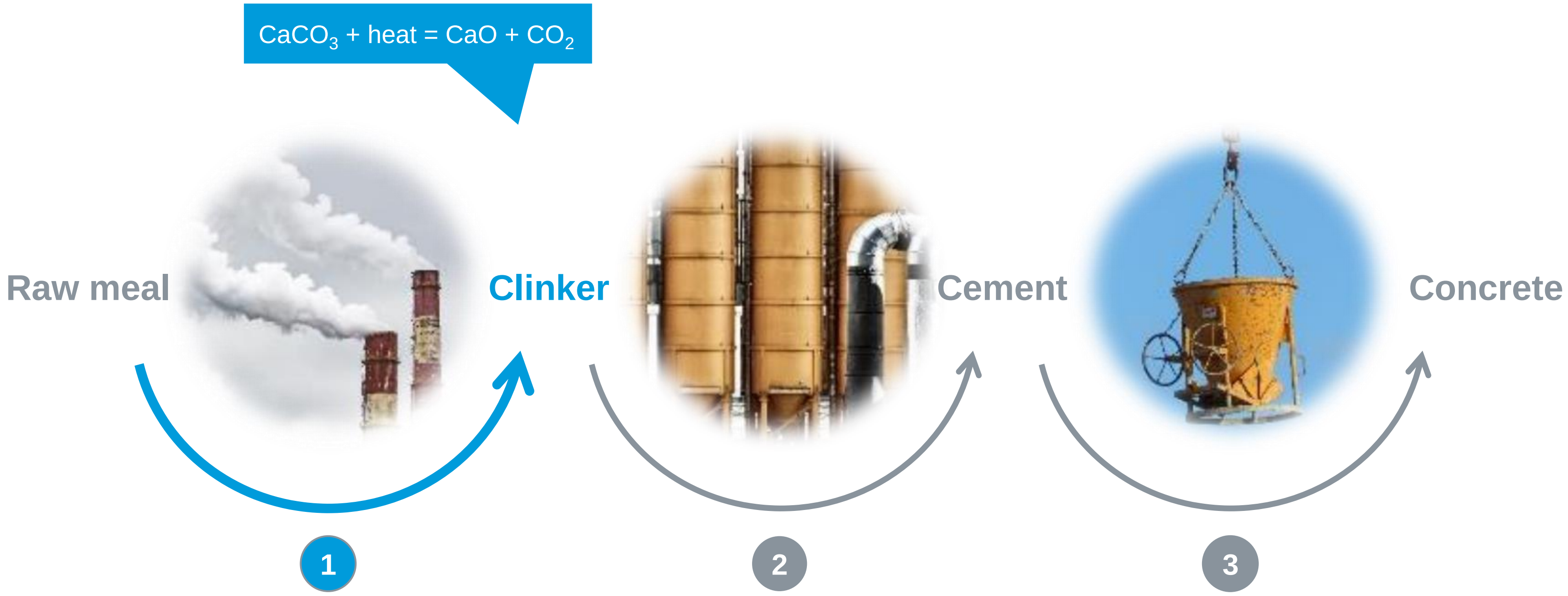
Clinker production accounts for ~80 to 90% of cement emissions

Cement/concrete production process



Clinker production (dry kiln)

1. **Preheating:** Raw meal of crushed limestone and small amounts of other minerals is preheated to around 900°C in a series of vertical cyclones with exhaust gases from the kiln.
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. This turns the meal into clinker.

Observations

- The calcination of limestone and the combustion of fuels used to bring limestone to the necessary heat account for **80 to 90% of the cement and concrete sector**.
- **Wet kilns are rapidly being phased out**, with over 80% of global and 90% of European clinker production now using dry kilns.
  - 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**, as more energy is required to evaporate the water contained in the slurry.

Note: *The production process shown assumes dry-kiln processing, which has widely replaced wet-kiln processing globally.
Sources: Portland Cement Association (2024), CEMBUREAU (2021), Mission Possible Partnership (2023)
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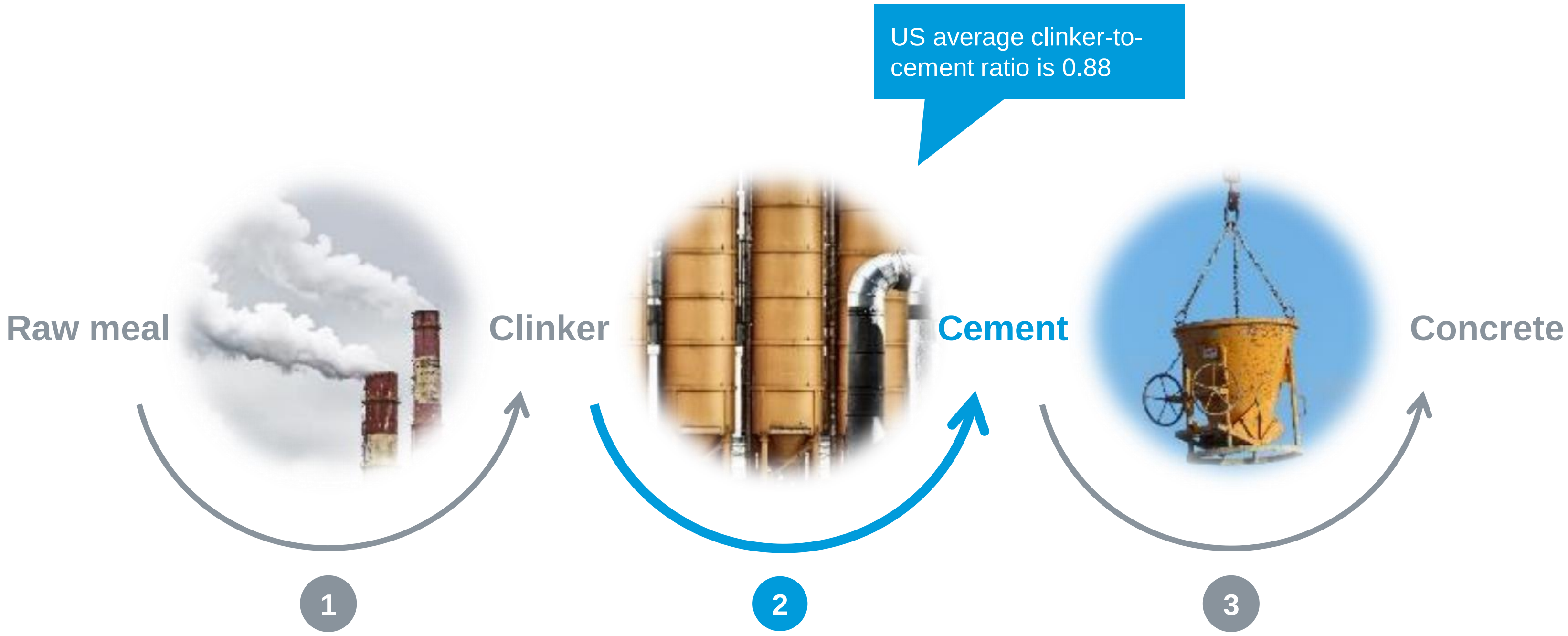
Energy emissions from cement grinding account for ~5% of the sector's emissions

Cement/concrete production process



Cement production

1. **Cooling:** Hot clinker is rapidly cooled to 100°C with air blowers powered by electricity.
2. **Grinding and blending cement:** Clinker is mixed with 4 to 5% gypsum and, in some cases, other supplementary cementitious materials (SCMs), including waste byproducts such as slag and fly ash or other natural materials such as clay. The mixture is ground and blended into cement.

Observations

- Energy emissions from cement grinding account for ~5% of the sector's emissions.
- The average **clinker-to-cement ratio in the US is 0.88** (880 kilograms of clinker per tonne of cement) while the **world average is 0.76**.
  - The US uses a lower proportion of SCMs than other countries.
- Ordinary Portland cement (OPC) can contain **up to 95% clinker**.
- Portland-limestone cement (PLC) is a modified formulation of OPC that contains up to 15% of added uncalcined limestone by mass, reducing carbon emissions by 10%, and can be used as a 1:1 replacement.

Note: *The production process shown assumes dry-kiln processing, which has widely replaced wet-kiln processing globally.
Sources: Portland Cement Association (2024), CEMBUREAU (2021), Mission Possible Partnership (2023), IEA (2023)
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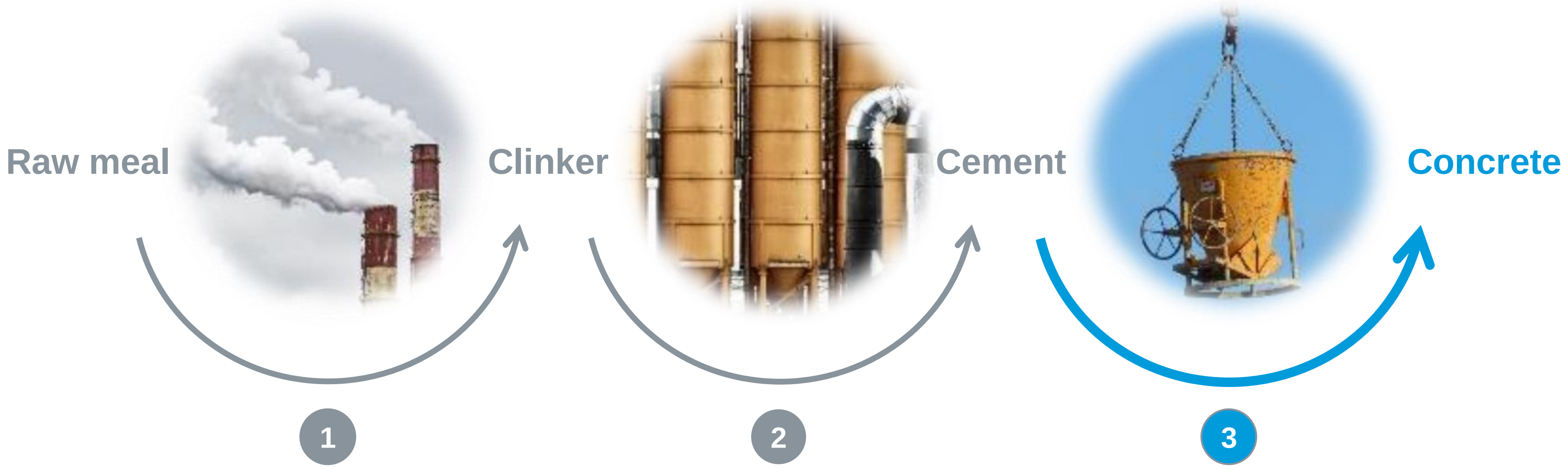
Energy emissions from concrete mixing and transportation accounts for ~5% of the sector's emissions

Cement/concrete production process



Concrete production

1. **Mixing concrete:** Cement is mixed with water and aggregates including crushed stone, gravel, and sand to make concrete.

Observations

- Energy emissions from concrete mixing and transportation account for ~5% of the sector's emissions.
- Concrete is usually made at a construction site or near one (an average of 50 kilometers away).
- Cement comprises **10 to 15% of concrete by weight**.
- 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.

Note: *The production process shown assumes dry-kiln processing, which has widely replaced wet-kiln processing globally.
Sources: Portland Cement Association (2024), CEMBUREAU (2021), Mission Possible Partnership (2023)
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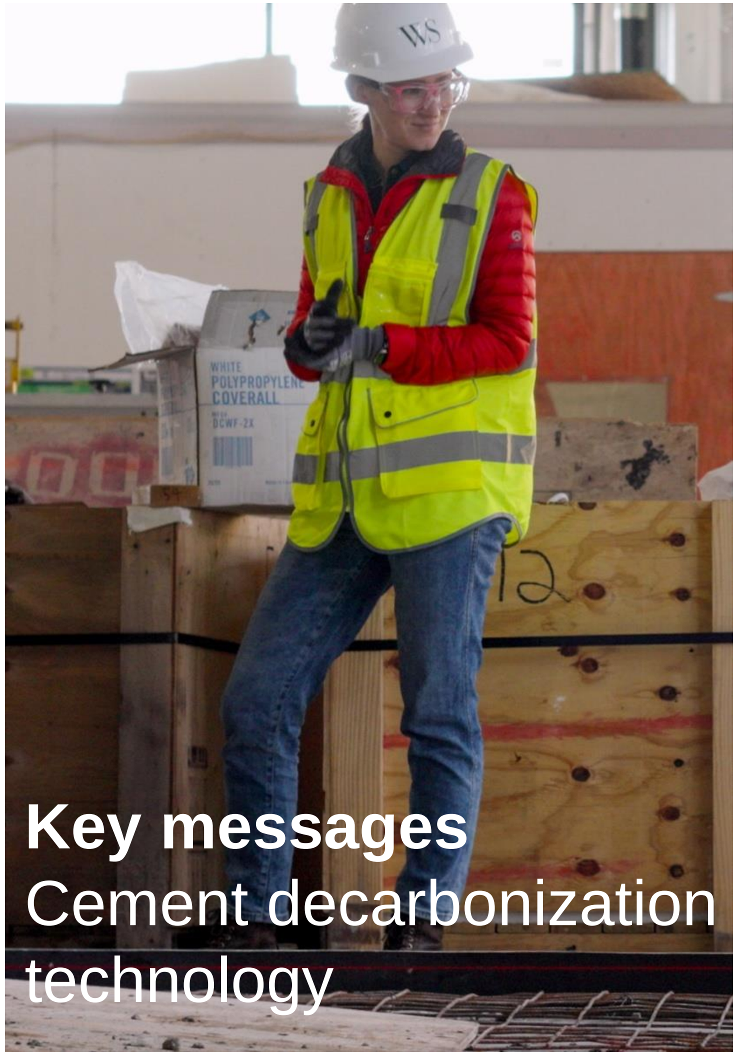
Cement Decarbonization Technologies



Key messages
Cement decarbonization technology

Decarbonization of cement production presents a significant technical challenge, as **over 80% of emissions are related to the chemical process and high thermal heat requirements**.

Various decarbonization strategies are being pursued across the cement and concrete value chains to drive adoption of low-carbon cement and concrete.

There are currently several deployable measures:

1. **Clinker substitution** to reduce the amount of clinker in cement, which lowers energy use, reduces pollutants, and reduces raw material consumption.
2. **Energy-efficiency** improvements to cement manufacturing facilities such as kiln electrification.
3. Switching to **alternative fuels** that are less carbon intensive than fossil fuels for heating kilns.

There are also more nascent technologies that have the potential to fundamentally reduce CO_2 but are yet to be demonstrated at a commercial scale:

4. **Alternative production methods** for OPC drop-in replacements like alternative feedstock and electrochemical reactions are still nascent.
5. **Alternative binder chemistries** are furthest from widespread commercial deployment.
6. **Carbon capture, utilization, and storage (CCUS)** projects in the cement sector to date have been **small-scale demonstration projects** of retrofits and integrations into new builds. However, further capital investment is required to enable **full-scale deployments**.

Current deployable measures combined can abate ~40% of cement industry emissions by 2050

Major technology type of cement decarbonization

Potential approach	1 Clinker substitution	2 Energy efficiency	3 Alternative fuels	4 Alternative production methods	5 Alternative binder chemistries	6 CCUS
Abatement potential*	30-40%	Up to 20%	1-8%	25-100%	25-100%	85-99%
Cost ($/tonne of cement)	-5 to -25	0 to -5	5 to -5	N/A, emerging technologies	N/A, emerging technologies	25 to 55
Deployment timeline	~ 2030	~2030	~2030	~ 2040	~2050	~ 2040
TRL**	7 to 9	9	9	3 to 5	3.5 to 9	6 to 7.5
ARL***	2 to 7	5 to 9	4 to 5	1	1	1
Status	• Broadly high TRL, deployment-ready, and economically viable today			• High abatement potential, not yet demonstrated at commercial scale, requires further technological maturity and customer acceptance		
Pathway to commercial scale	• Rapid deployment, incentivized by demand signal from large buyers and enabled by accelerated validation of low-carbon blends			• Accelerated buildout of greenfield plants, enabled by cost reductions and coordinated procurement to create investable demand signal • CCUS enabled by tax credits, policy support, and cost reductions as deployments ramp		

Observations

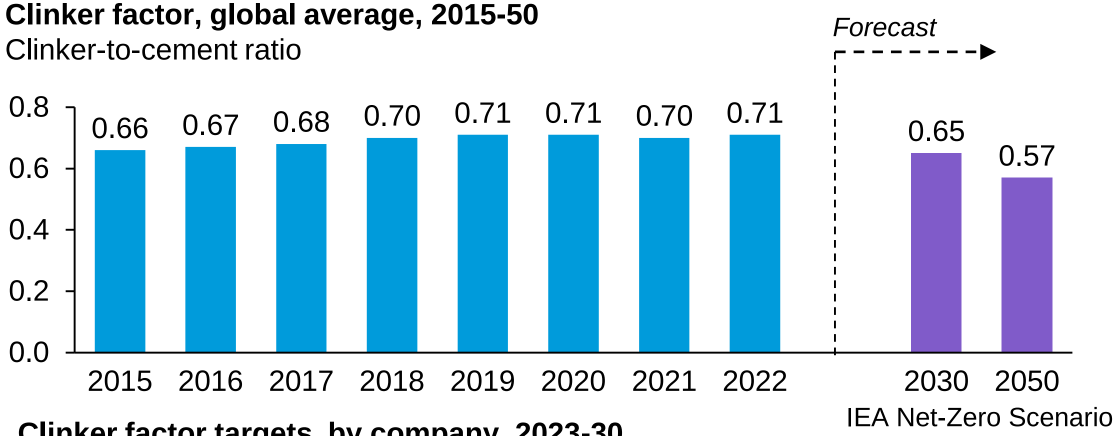
- Current deployable measures **can abate ~30% of emissions by the early 2030s and ~40% of emissions by 2050**, while the remaining ~60 to 70% of emissions will require other technologies.
- Key technologies have performance and cost uncertainty.
- Decarbonization approaches may come with structural cost increases; however, many of the currently deployable measures are cost saving.

Notes: * Unconstrained abatement potential for a given tonne of cement produced for each approach in isolation; ** Technology Readiness Level (1-9) measures the maturity of evolving technologies; *** Adoption Readiness Level (1-9) measures factors for private-sector uptake beyond technology readiness, including value proposition, market acceptance, resource maturity, and license to operate.
Source: Department of Energy Liftoff Report (2023)
Credit: Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

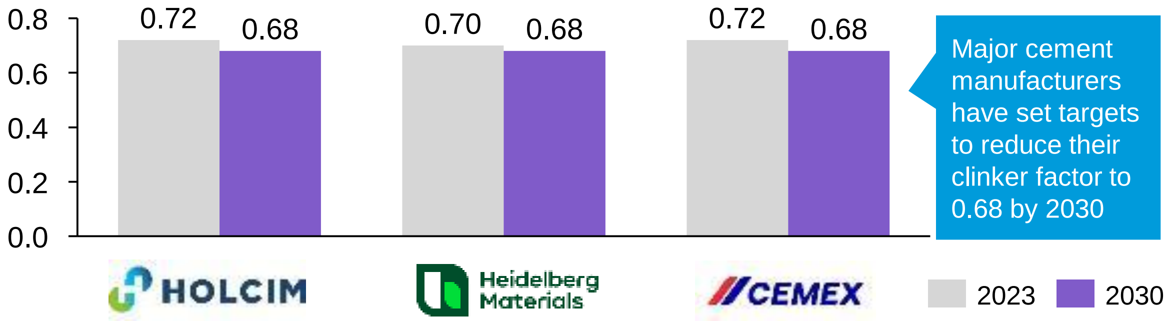
1 Clinker substitution technologies can lower energy use, reduce pollutants, and reduce raw material consumption

Clinker substitution technologies

Clinker factor, global average, 2015-50
Clinker-to-cement ratio



Clinker factor targets, by company, 2023-30
Clinker-to-cement ratio



Reducing the clinker-to-cement ratio

- Reducing the clinker-to-cement ratio (clinker factor) by substituting a proportion of clinker for supplementary cementitious materials (SCMs) can reduce emissions.
- This varies considerably by region due to the **availability of materials and varying requirements and policies for product specifications**.
  - China has one of the lowest ratios globally at 0.65 in 2022.
  - The US and Canada have high ratios: 0.89 and 0.86, respectively.
  - In Europe, the average clinker-to-cement ratio is 0.77.

SCMs and fillers

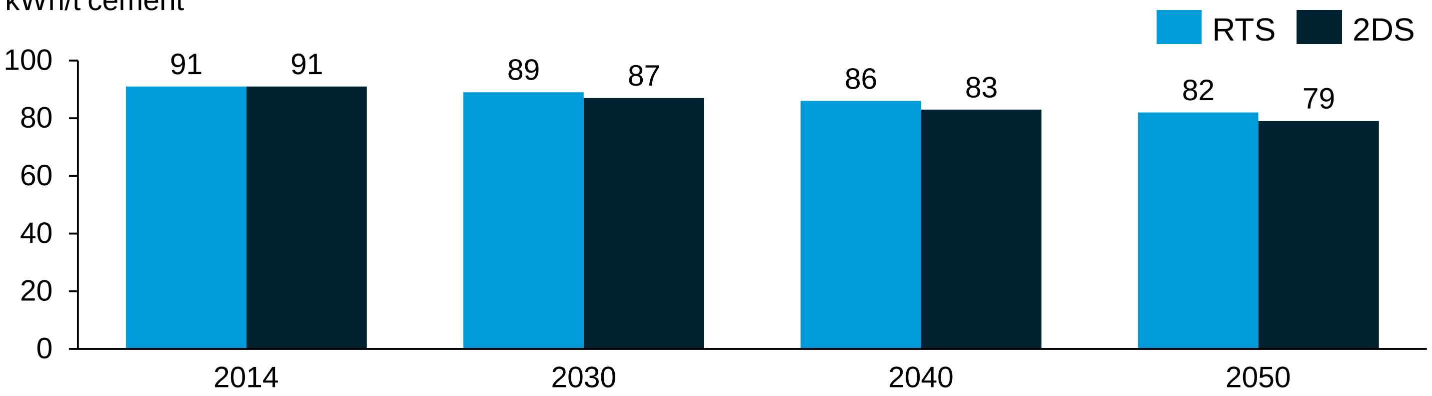
- SCMs and fillers can be used to partially replace clinker* and enable use of industrial waste products, such as:
  - **Fly ash** (a byproduct of coal-fired power generation) is commonly used as a 20 to 30% cement replacement in cement and concrete. It can improve the durability, workability, and long-term strength gain of concrete.
  - **Blast furnace slag** (a byproduct of iron and steel) can be used as a 30 to 65% cement replacement in cement and concrete. It can increase the strength and durability of concrete.
  - **Silica fume** (a byproduct of silicon metal) can increase the compressive strength and durability of concrete; however, substitution rates are very low.
  - **Limestone** can be finely ground to supplement clinker in cement and concrete.
- However, availability of these industrial byproducts may decline when these industries decarbonize.

Notes: *In some countries, SCM substitution occurs during concrete manufacturing rather than cement manufacturing.
Sources: IEA (2023), Congressional Research Service (2023), Global Cement Magazine (2024), International Cement Review (2024), Heidelberg (2024), Cemex (2024), Holcim (2024), IEA Net Zero by 2050 (2021)
Credit: Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Isabel Hoyos, Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

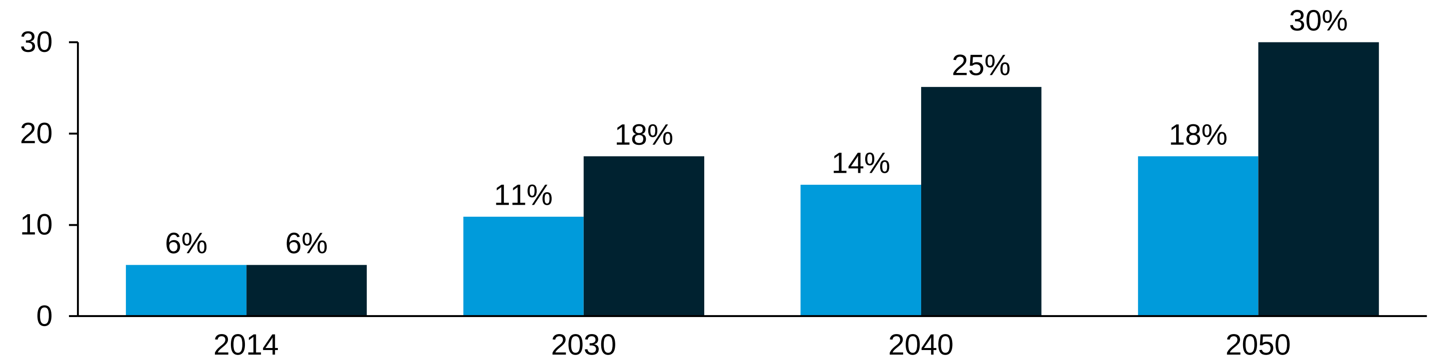
② ③ Reduced electricity intensity and increased alternative fuel use significantly cut CO_2 emissions in cement under RTS and 2DS scenarios

Energy-efficiency measures: Global cement industry

Electricity intensity of cement, 2014-50
kWh/t cement



Alternative fuel use, 2014-50
Percentage of thermal energy consumption



Source: IEA Technology Roadmap (2018)
Credit: Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

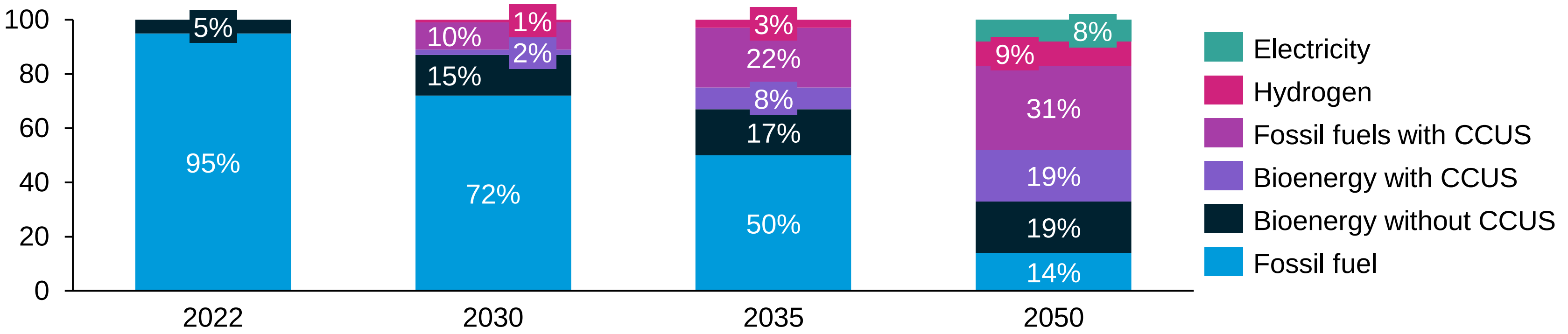
Enhancing energy efficiency under RTS and 2DS

- **Reference Technology Scenario (RTS) projects a 4% increase in direct CO_2 emissions** from the cement industry by 2050, despite a 12% rise in global cement production.
  - RTS serves as a baseline scenario and considers energy consumption trends and national commitments, including NDC pledges, to limit carbon emissions and improve energy efficiency.
  - This represents a considerable shift from the business-as-usual approach.
- **2°C Scenario (2DS) aims for a 24% reduction in global direct CO_2 emissions** by 2050, despite an expected increase in global cement production.
  - 2DS outlines an energy system pathway and a CO_2 emissions trajectory to limit global temperature rise to 2°C by 2100.
  - Annual energy sector CO_2 emissions will be reduced by ~60% from current levels by 2050.
  - This represents an ambitious transformation of the global energy system, requiring significantly stronger response.
- Both scenarios assume **reliance on commercially available or demonstration-phase technologies**, with no hindrance from nontechnical barriers like social acceptance, regulatory issues, or information deficits.

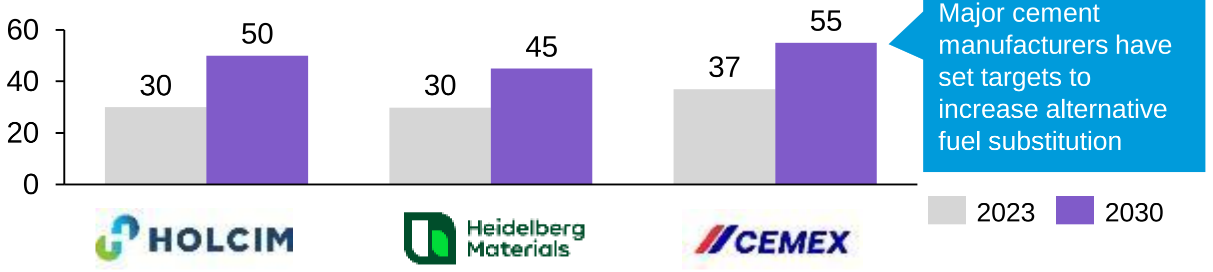
3 A shift from fossil fuel to alternative fuels for heating kilns will be required for cement production

Fossil fuels account for over 90% of thermal energy needs in 2022

Share of low-emissions fuel in thermal energy use, 2022-50
Percentage



Alternative fuel substitution rate targets by company, 2023-30
Percentage



Observations

- **Coal dominates cement production fuel use at 70%**, followed by oil and natural gas at 24%, while alternative fuels (biomass and waste) contribute just 5% to global thermal energy consumption during cement production.
- Switching to alternative fuels that are less carbon intensive than conventional fuels **delivers 0.9 Gt CO_2 or 12% of the cumulative CO_2 emissions savings** by 2050 globally under the IEA 2°C Scenario.
- **Waste fuels and biomass are technologically mature** (some wastes, like tires, are already used as fuel for kilns today) and can generally be **deployed without significant cost impact** (potentially -$1 to $1 of impact per tonne of cement in the absence of policy or other market incentives), but abatement potential is limited and deployment comes with supply constraints.

Sources: IEA (2023), Global Cement Magazine (2024), International Cement Review (2024), Heidelberg (2024), Cemex (2024), Holcim (2024)

Credit: Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Holcim invests in emissions reduction through Geocycle co-processing and low-carbon cement/concrete products

1

ECOPact
The Low-Carbon Concrete

ECOPlanet
The Green Cements

30% less carbon emissions compared to OPC

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.
- Holcim **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:** By recycling construction demolition materials, using innovative materials like calcined clay, pozzolana, and reclaimed ashes, and processing industrial waste
- **Calcined clay to replace limestone-based clinker**

3

geocycle

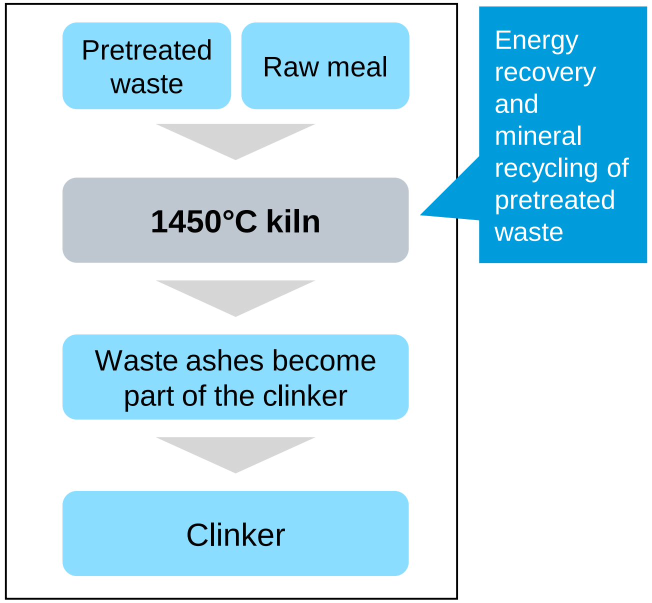
13.9 million tons of waste recycled in 2023

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

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 it at high temperatures, the **minerals found in 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.

Co-processing in cement plants



4 Alternative production methods are still nascent, will potentially require ~$0.5B to $1B of CapEx for deployment per plant

Alternative production methods

	Alternative feedstocks	Electrochemical production systems	Other novel production methods
Description	• Using non-carbonate rocks as feedstocks allows these production methods to avoid the process emissions of conventional cement production. • Alternative feedstocks include silicate rocks and fly ash.	• Using electrochemical reactions to turn non-carbonate rocks into alternative cement products avoids the process emissions of conventional cement production.	• Other novel approaches to cement production rethink the cement production process to either avoid or reabsorb carbon emissions.
Leading companies and technologies	BRIMSTONE ECOMATERIAL TECHNOLOGIES Sublime Systems		fortera Furno CALPORTLAND* BIOMASON

Observations

- Alternative production methods must yield products **close enough to drop-in replacements for OPC** and require cost reductions and public financial support to reach **widespread commercial viability**.
- Deployment will **require an estimated ~$0.5 billion to $1 billion CapEx investment per plant** and, depending on the technology, an OpEx premium from increased energy consumption.

Note: *CalPortland is licensing Solidia's patent to produce low-limestone cement and concrete with up to 50% less carbon emissions.
Sources: Department of Energy Liftoff Report (2023), WRI (2024)
Credit: Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

4 Sublime replaces carbon-intensive limestone with calcium silicate-based feedstocks to produce cement electrochemically

Sublime Systems

Founded: 2020, Massachusetts, US

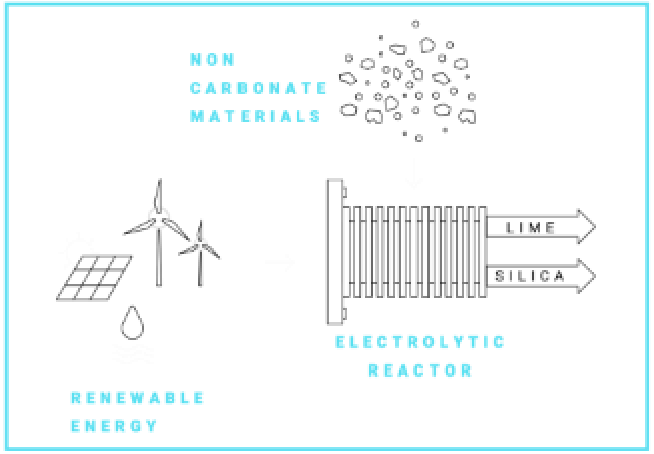
Total funding raised to date: $45.9 million

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 to produce its end product, a calcium silica cement to displace ordinary Portland cement (OPC).

Current achievements

- Awarded the Industrial Demonstrations Program $87 million federal award in March 2024, to build a new, ultralow-carbon cement manufacturing facility in Holyoke, Massachusetts, Sublime's first commercial manufacturing scale-up.
- Received a life cycle assessment (LCA) validating that its cement manufacturing process can reduce 90% of greenhouse gas emissions. Sublime's cement has a global warming potential of 72 kg of CO_2 per tonne of cement, while OPC is 922 kg of CO_2 per tonne of cement.



Sources: Sublime (2024), Advanced Research Projects Agency-Energy (ARPA-E) (2024), Department of Energy (2024)
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4 Brimstone eliminates the calcination process in traditional cement production by using carbon-free calcium silicate rocks

BRIMSTONE

Founded: 2019, California, US

Total funding raised to date: $60 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 creates both ordinary Portland cement (OPC) and supplementary cementitious materials (SCM) in one process. The cement contains magnesium, calcium, silicon, iron, and aluminum, absorbing CO_2.

Current achievements

- Awarded a March 2024 Industrial Demonstrations Program $189 million federal award, to finance construction of a commercial-scale plant to produce 140,000 metric tonnes per year of decarbonized industry-standard OPC and SCM as well as other co-products.
- Received third-party certification that its cement meets or exceeds ASTM C150 standards for OPC.

Uses calcium silicate rocks with magnesium

Creates OPC and SCMs in one process

Sources: Brimstone (2024), Advanced Research Projects Agency-Energy (ARPA-E) (2024), Department of Energy (2024)

Credit: Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

4 Eco Material Technologies produces near-zero carbon ‘pozzolanic cement’ with proprietary fly ash pretreatment

ECOMATERIAL TECHNOLOGIES

Founded: 2022, Utah, US

Total funding raised to date: $125 million

Technology

- Eco Material Technologies uses a **proprietary physical and chemical pretreatment of fly ash** — 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

- Fly ash is a waste product of coal-fueled power plants, which are being retired across the US and globally.
- Fly ash is produced at coal plants, not where they are needed for construction materials, and their low value makes shipping challenging.

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.

Time (days)	Control cement	50% PozzoSlag®/ 50% control cement
1	2,742 psi	2,417 psi
3	4,092 psi	4,467 psi
7	5,195 psi	5,367 psi
14	5,272 psi	6,715 psi
28	5,827 psi	6,975 psi
56	6,567 psi	9,217 psi

Sources: Eco Material (2024), Green Cement (2024), Forbes (2023)

Credit: Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

4 Fortera's ReCarb process is a bolt-on technology that works with existing infrastructure to manufacture low-carbon cement

fortera

Founded: 2019, California, US

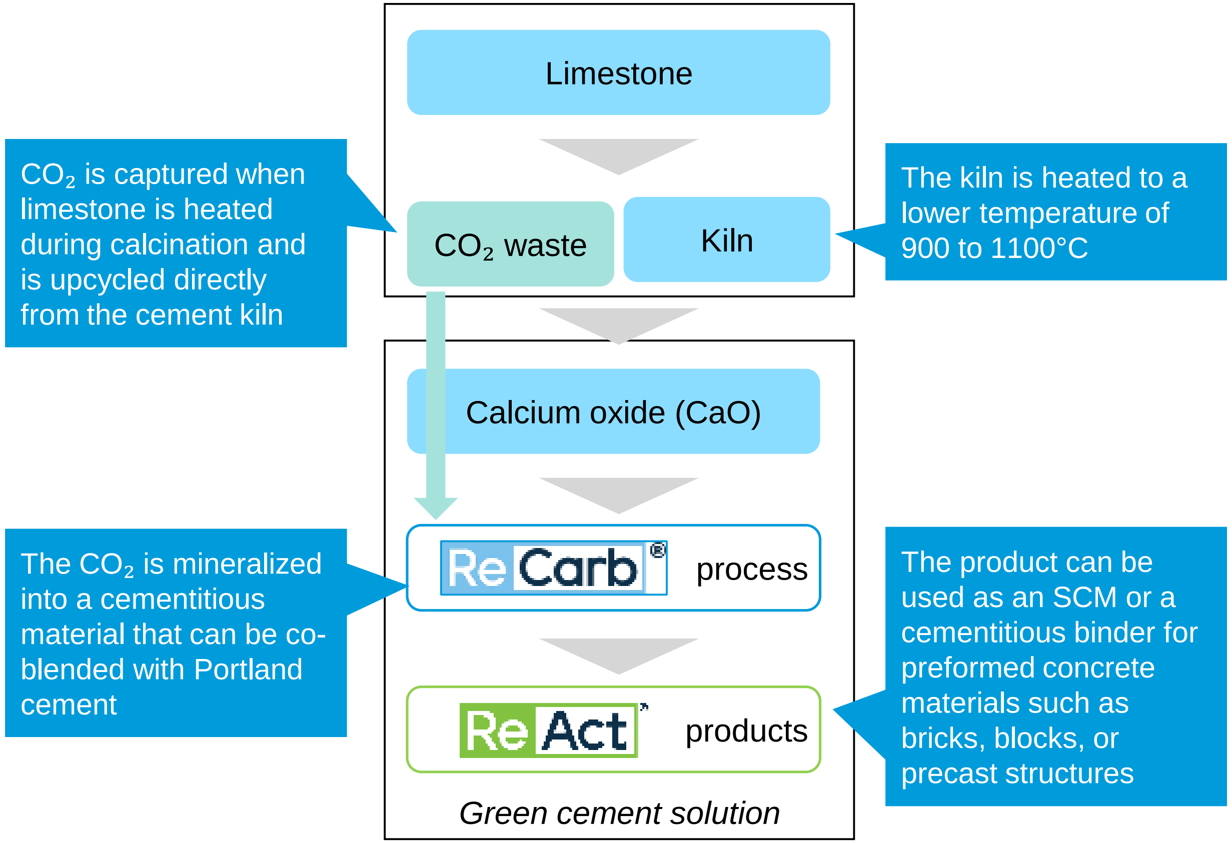
Total funding raised to date: $104 million

Technology

- Fortera developed a **bolt-on decarbonization solution** that **integrates into existing cement plant infrastructure** to produce low-carbon cement.
- Fortera captures carbon dioxide emitted during cement production and **permanently sequesters it by mineralizing** the CO_2 into ready-to-use cement through its ReCarb process.

Current achievements

- In April 2024, Fortera opened its **first industrial green cement** and carbon mineralization facility adjacent to CalPortland's cement plant in Redding, California.
- The facility aims to produce 15,000 tonnes of ReAct low-carbon cement annually and capture 6,600 tonnes of CO_2, **reducing emissions by 70% compared to traditional methods**.



Sources: Fortera Global (2024), Global Cement (2021), Business Wire (2024)

Credit: Jessica Cong, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

4 Biomason has developed a biocement alternative to reduce CO_2 emissions

Founded: 2012, North Carolina, US

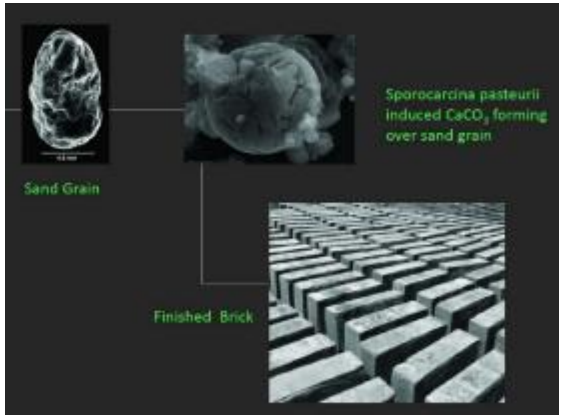
Total funding raised to date: $95 million

Technology

- Biomason builds calcium carbonate biocement® by **combining aggregates with bacteria, nutrients, calcium, and carbon sources**.
- Its nature-inspired technology **sequesters carbon and eliminates high-energy emissions**.
- Biomason aims to eliminate 25% of the concrete industry's global carbon emissions by 2030.

Current achievements

- Biomason's Biolith® tile is made of 85% natural aggregates and 15% biocement.
- Biomason commissioned the world’s first biocement manufacturing facility in Ikast, Denmark, commencing commercial production in July 2023 through a partnership with Danish concrete manufacturer IBF.



4 CalPortland is licensing Solidia's patent to use less limestone to produce cement and concrete, with up to a 50% carbon reduction

CALPORTLAND®

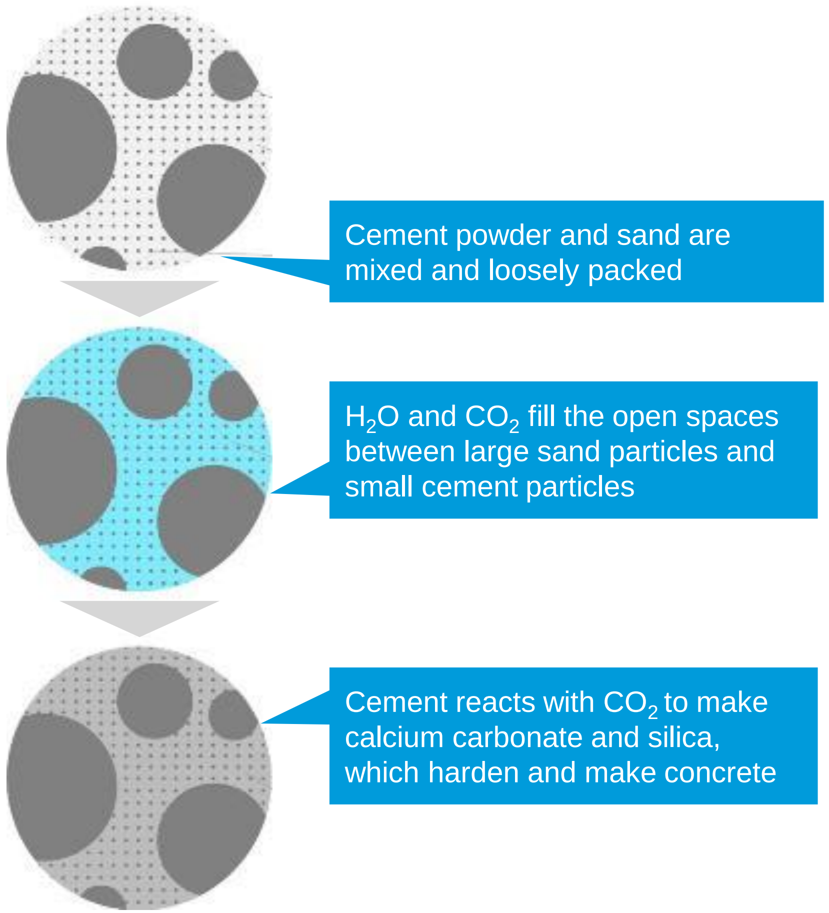
Licensing agreement: June 2024

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% carbon emissions reduction and concrete with up to 50% carbon emissions reduction.
- 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.



4 Furno has developed a modular, carbon-neutral, kiln and combustion technology for cement production

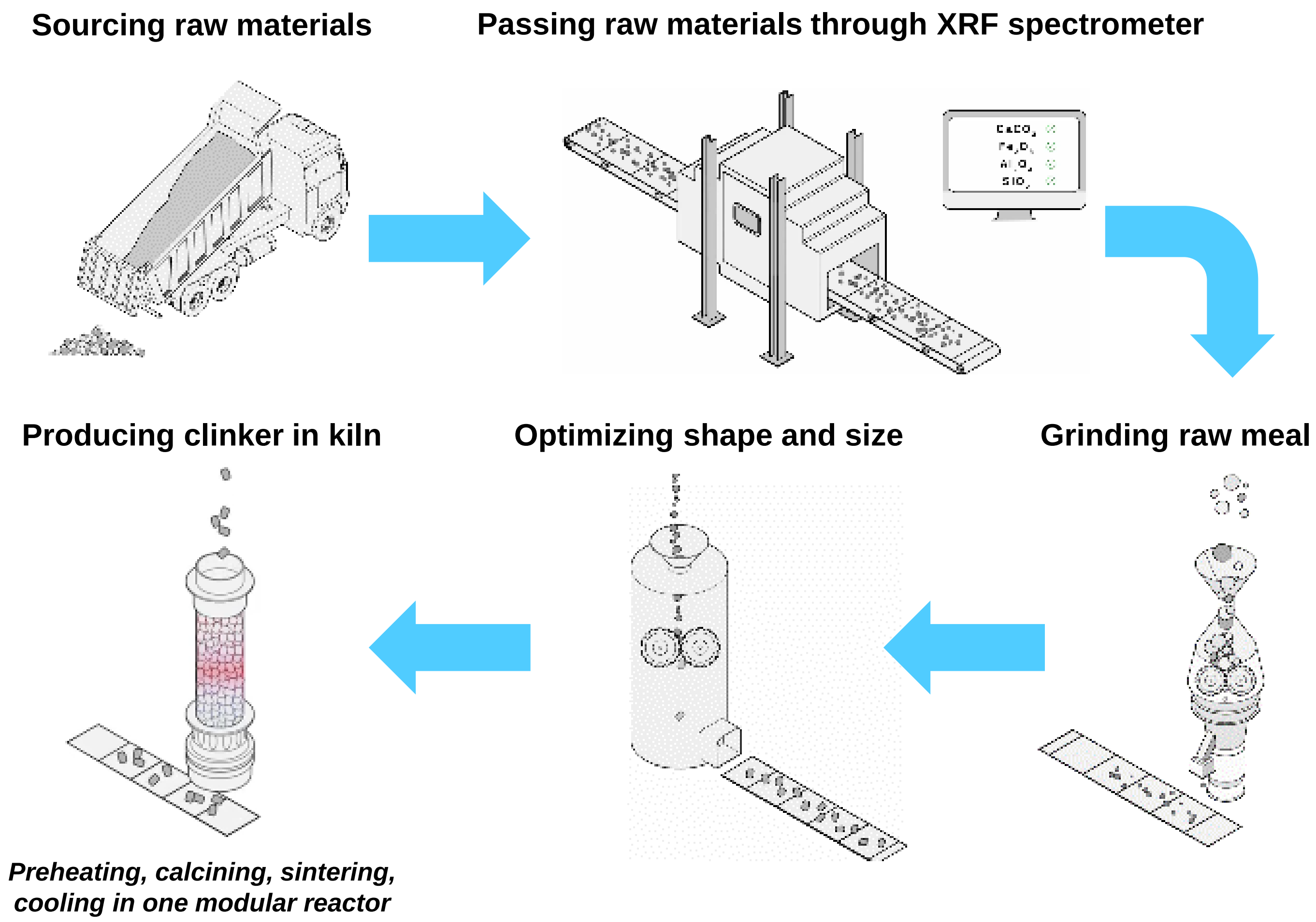
Furno

Founded: 2020, California, US

Total funding raised to date: $12.45 million

Technology

- Furno has developed the **world's first modular and carbon-neutral cement plant that scales on demand**.
- Furno's kiln and combustion technology uses gas-based fuels rather than solid fuels, which reduces 70% of fuel emissions from cement production, cutting energy costs in half.
- Its end-to-end cement production unit integrates four phases — preheating, calcining, sintering, and cooling — into one compact reactor and operates at over 80% thermal efficiency.
- Furno's plant design reduces capital and operational costs. This reduces barriers to entry for local or small-scale cement production, which enables cement production to meet demand where it exists and minimizes the need for transportation of materials.
- Combined with materials innovations, Furno eliminates 88% of emissions.



5 Alternative binder chemistries have the lowest technology and adoption readiness levels

Alternative binder chemistries

Maturity stage	**Pre-pilot and pilot**	**Small-scale commercial production**
Technologies	• Magnesium oxide cement derived from magnesium silicate (MOMS) • Pre-hydrated calcium silicate cement • Biomineralization • Engineered clinkers	• Reactive belite-rich Portland cement (RBPC) • Belite calcium sulfoaluminate (BCSA) cement • Alkali-activated binders

Observations

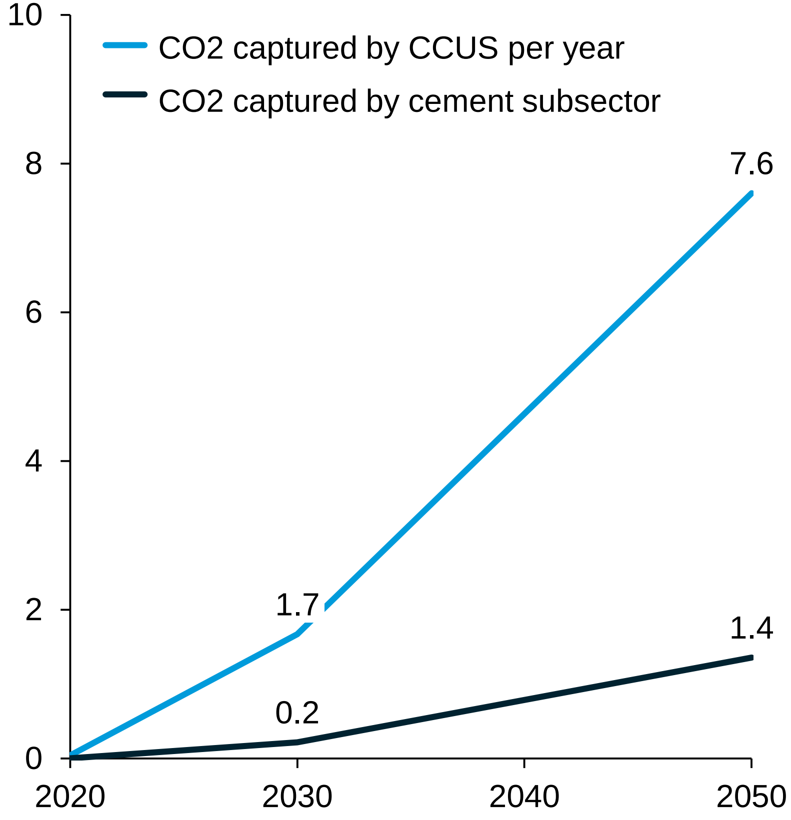
- Alternative binder chemistry technologies are **further from widespread deployment than alternative production methods** of cement. The Department of Energy estimates they may not achieve a sizable market share until 2040.
- Maturity stages range from pre-pilot R&D to small-scale commercial availability.
- **Accelerated adoption of performance-based standards** would enable deployment.
- Lower-risk, non-structural, precast, and decorative applications make up ~15% of the market and can **provide a niche for novel cements as they demonstrate safety, gain acceptance, and reduce costs**.

Sources: Department of Energy Liftoff Report (2023), GCCA (2024)

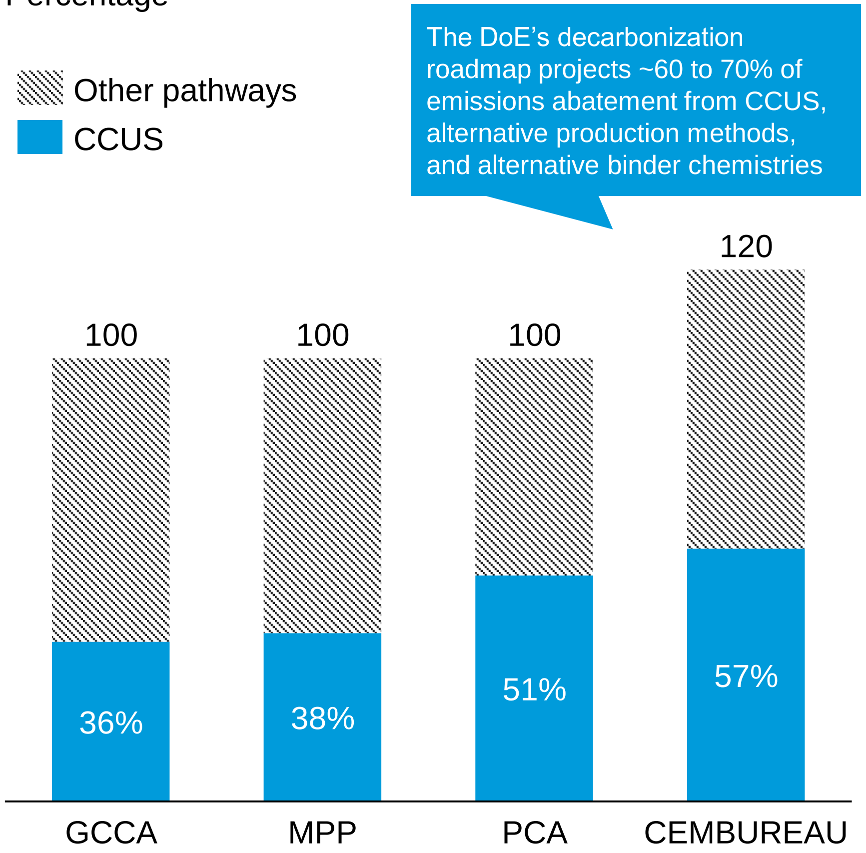
Credit: Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

6 Carbon capture, utilization, and storage (CCUS) is projected to abate cement sector emissions not abated by other technologies

IEA targets for CO_2 captured, 2020-50
Gt CO_2



Abatement from CCUS by decarbonization roadmap, 2050
Percentage



Observations

- **~55% of the cumulative emissions reductions from CCUS** rely on technologies that are currently at the demonstration or prototype stage.
- In April 2023, Heidelberg and the government of Canada committed to invest in the construction of the cement industry's **first full-scale net-zero carbon capture and storage facility** in Edmonton, Canada. It is expected to be **operational by late 2026** and capture over **1 million tonnes of CO_2 annually**.
- Heidelberg received Norwegian government funding in 2020 to build a **full-scale carbon-capture and storage facility** at its factory in Brevik. The aim of the project will be to reduce emissions by **400,000 tonnes of CO_2 annually**.
- In 2018, Chinese-based Anhui Conch invested $10 million into a carbon-capture project to capture **50,000 tonnes of CO_2 annually**; however, it is a "loss maker," as there is a **limited local market** for the captured CO_2.

Sources: IEA Net Zero by 2050 (2021), IEA (2023), Global Cement Magazine (2024), International Cement Review (2024), Heidelberg (2024), GCCA (2021), Mission Possible Partnership (2023), PCA (2024), DoE (2023), CEMBUREAU (2024)

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

Concrete value chain

Cement producers	Concrete producers	Concrete suppliers	Construction	End users
• Wholesalers • Retailers	• Wholesalers • Retailers	• Ready-mix companies • Precast companies • Vertically integrated contractors • Wholesalers • Retailers	• Contractors • Developers	• Government • Companies • Individuals

Observations

- Concrete is bought through **multiple layers of intermediaries**.
- **~70 to 75% of cement is used to make ready-mix concrete**, which can be prepared on site and is used in various applications including roads and buildings. This segment has stringent 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 US, **government procurement accounts for ~50% of concrete demand**, giving public sector spending a significant role in market-side decarbonization.

Sources: McKinsey (2020), Department of Energy Liftoff Report (2023), WRI (2024), PCA (2024)
Credit: Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Demand-side levers key for material efficiency

Levers for concrete decarbonization

	1 Efficiency in design and construction	2 Efficiency in concrete production	3 Recarbonation
Concrete decarbonization lever	• Optimizing use of concrete in construction using material-efficient design and construction (e.g., smart design systems, choice of concrete floor slab geometry, concrete column spacing, optimization of concrete strength)	• Transitioning from small-project site batching of concrete using bagged cement to industrialized processes offers emissions savings because of the adherence to mix specifications and quality control.	• Recarbonation is a natural process of CO_2 uptake by concrete. Concrete reabsorbs a significant amount of CO_2 over its lifetime as a permanent CO_2 sink. • **12 to 23%** of process emissions released during cement production can be absorbed.
Pathway to decarbonization	• CO_2 emissions would need to become a design parameter for construction projects • Can be applied with current standards and regulations	• Transition to industrialized production has been implemented in some countries. • Use of admixtures improved processing of aggregates.	• Would need to facilitate access to concrete demolition waste to enable the industry to maximize CO_2 uptake.
% contribution to achieve net zero in 2050 (GCCA)	22%	11%	6% (recarbonation only)
CO_2 emissions savings in 2050 (GCCA), 3.830 metric tonnes (total)	840 Mt CO_2	430 Mt CO_2	242 Mt CO_2 (recarbonation only)

Observations

- **Efficiency strategies in design and construction** can be a significant lever to reduce overall consumption of cement.
- **Optimization of concrete production** through a transition to industrialized production can reduce demand for cement.
- **Recarbonation** and improved management of end-of-life materials could offer additional mitigation opportunities for circular concrete.

Sources: Climate Works (2021), GCCA Concrete Future (2021), IVL methodology (2021), Nature Communications (2024)
Credit: Jessica Cong, Isabel Hoyos, Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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

3D printing applications

Holcim, GE Renewable Energy, and COBOD will undertake a multiyear collaboration to develop 3D-printed concrete bases for wind turbines that can reach heights up to 200 meters. Traditionally built in steel or precast concrete, these have typically been limited to 100 meters, as the base cannot exceed the 4.5-meter diameter that can be transported by road without excessive additional costs.

14Trees, a joint venture between Holcim and British International Investment, launched Africa’s largest 3D-printed affordable housing project in Kilifi, Kenya, in 2021. In 2023, the printing of the first 10 housing units in the 52-house complex were successfully completed.

In 2022, Cemex and COBOD announced a proprietary admixtures family called D.fab, the first 3D printing solution that uses conventional ready-mix concrete in the building process. The technology can deliver significant savings versus traditional 3D-printing construction methods and materials.

Description

- 3D construction printing can be used to create the same functional units with less materials.
- Cement manufacturers have been involved in projects or research and development related to 3D printing technology.

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)

Adoption Trends and Obstacles

Key messages
Adoption trends and obstacles

Decarbonizing cement production is a complex process, requiring coordinated efforts across technological innovation, policy support, and market adaptation.

Many potential decarbonization approaches for cement production face challenging paths to scale due to several factors, such as:

- **Technology, performance, and cost uncertainty**
- **Investment and financing constraints** that hinder attracting capital at the required scale
- **Slow adoption** of new technologies to change traditional industry practices

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The EU has introduced policies to support the industry's transition to net zero:

- The Carbon Border Adjustment Mechanism (**CBAM**) and EU Emissions Trading System (**ETS**) free allowances phase-out will start from 2026
- The EU Innovation Fund, which has awarded funding to support 12 cement projects, primarily in CCUS

The US has introduced several policies and initiatives at the federal and state levels, including:

- **The Federal Buy Clean Initiative** for purchasing low-carbon concrete to significantly reduce emissions in federal projects

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Policy frameworks in the Asia-Pacific region, which produces about 70% of the world's cement, are still underdeveloped.

- Robust policies are crucial to meet growing demand while achieving decarbonization goals.
- Lack of comprehensive policies in key markets like India and China significantly impedes efforts to reduce carbon emissions and improve environmental performance.

Key stakeholders face different challenges in decarbonization efforts across the cement and concrete value chain

	Cement producers	Concrete producers	Concrete suppliers	Construction	End users
A Technological	High energy requirements, limited availability of cost-effective, industrial-scale CCUS technologies	Ensuring consistent quality when using supplementary cementitious materials (SCMs) and alternative binders	Adapting logistics and distribution systems to handle low-carbon concrete	Integrating new low-carbon materials into existing construction practice	
B Financial	High initial CapEx required for retrofitting plants with low-carbon technologies	Higher production costs associated with using low-carbon materials.	Higher costs impacting profitability	Higher upfront costs for using low-carbon materials	Higher costs for buildings and infrastructure
C Policy	Navigating inconsistent regulatory frameworks and standards			Insufficient financial incentives or regulatory mandates to encourage large-scale adoption of low-carbon technologies	Lack of awareness about the importance and benefits of low-carbon materials
D Market	Limited supply of raw and alternative material, e.g., SCMs, fly ash		Convincing construction companies and end users to adopt low-carbon concrete		
E Operational	Lack of infrastructure for transporting and storing captured CO_2	Managing logistics for transporting low-carbon concrete with different handling and curing requirements		Training workers to handle and work with new materials	Higher market prices

Sources: McKinsey (2020), Department of Energy Liftoff Report (2023), WRI (2024), PCA (2024)

Credit: Shailesh Mishra, Jessica Cong, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

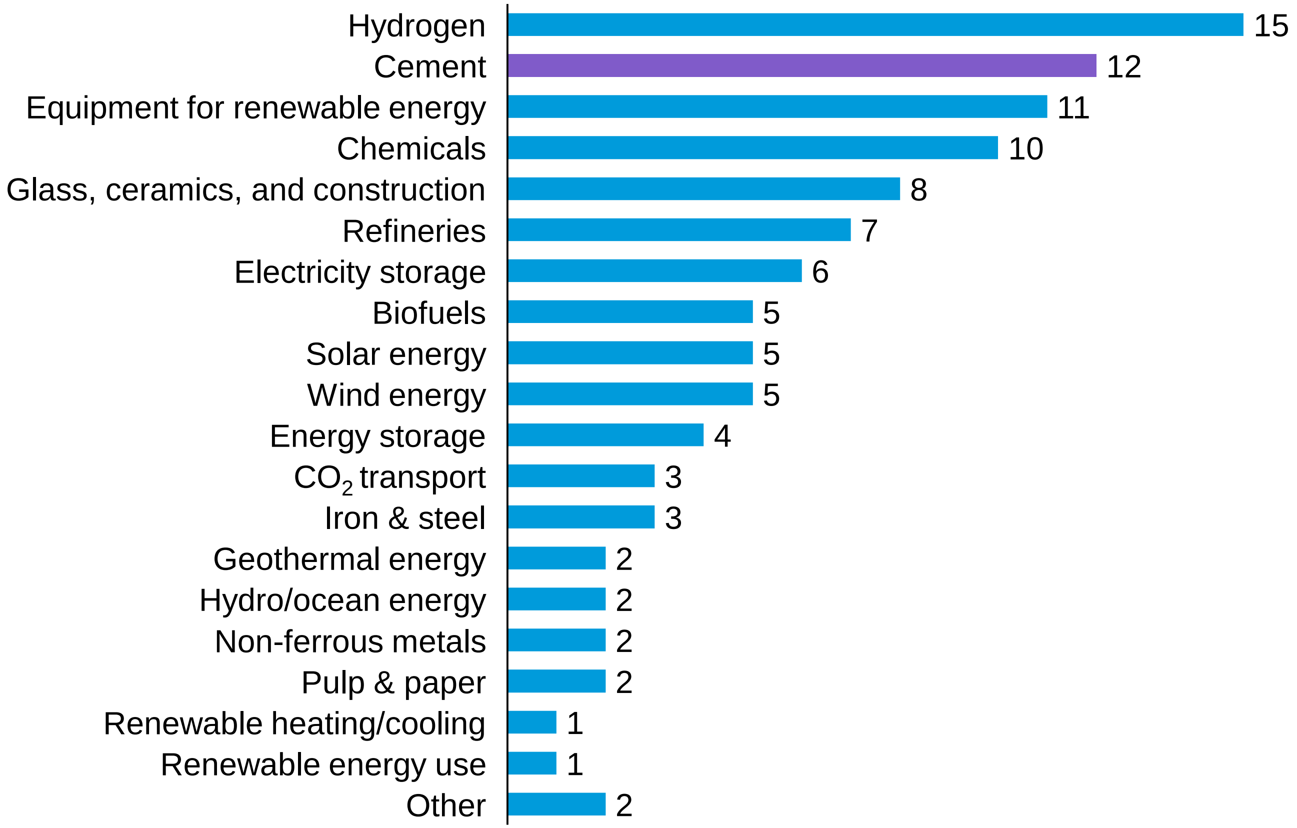
A broad range of policy instruments have been implemented to decarbonize cement manufacturing

Enabler	Policy type	Policy instrument	Key examples	Impact
Risk management	Risk-sharing	Financial certainty to innovators (through subsidy and incentives)	• EU Carbon Contracts for Difference • US 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 create 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 US • 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 • US General Services Administration low embodied-carbon concrete standards in the US	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 US and the EU
Capital	Incentive-based	Tax credits/subsidies	• CCUS tax credits under IRA	**20 to 30%** reduction in costs to deploy CCUS in cement plants

Sources: WEF (2023), Climate Bond Initiative (2023), EU Innovation Fund (2024), EU Net-Zero Industry Act (2024), EU ETS (2024), California ETS (2024), EU CBAM (2024), GPP Pledge (2023), Federal Buy Clean Initiative (2024), IRA 45Q, EU CCfDs, DoE's Industrial Demonstrations Program

The EU Innovation Fund has invested in 12 cement projects for the demonstration of innovative low-carbon technologies

Number of projects EU Innovation Fund has invested in (April 2024)



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 April 2024, **12** out of **106** projects funded by the EU Innovation Fund (US$43.6 billion) are cement-related projects, totaling **US$2.1 billion** in investment.
- Though all cement projects have different technology installations, they **all have CCUS installation plans** as part of the projects.

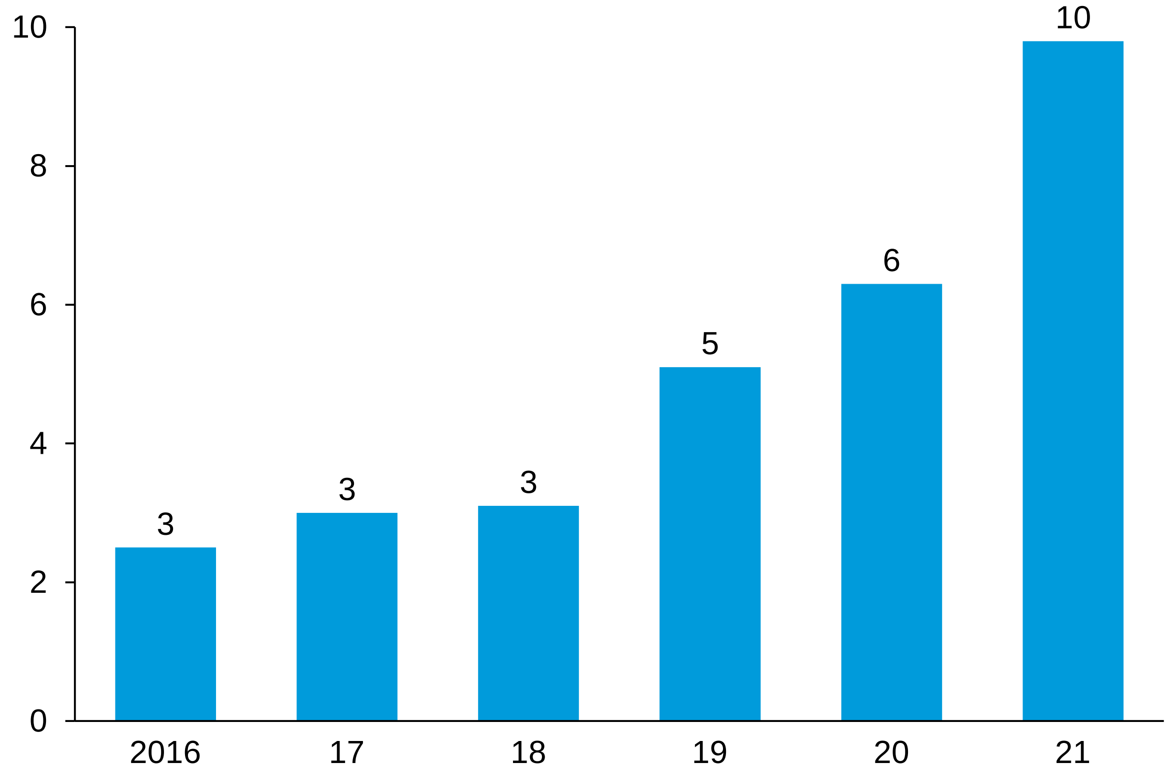
Source: EU Innovation Fund (2024)

Credit: Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

The EU's climate policy reforms to phase in CBAM and phase out free allocations of ETS will directly impact the cement sector

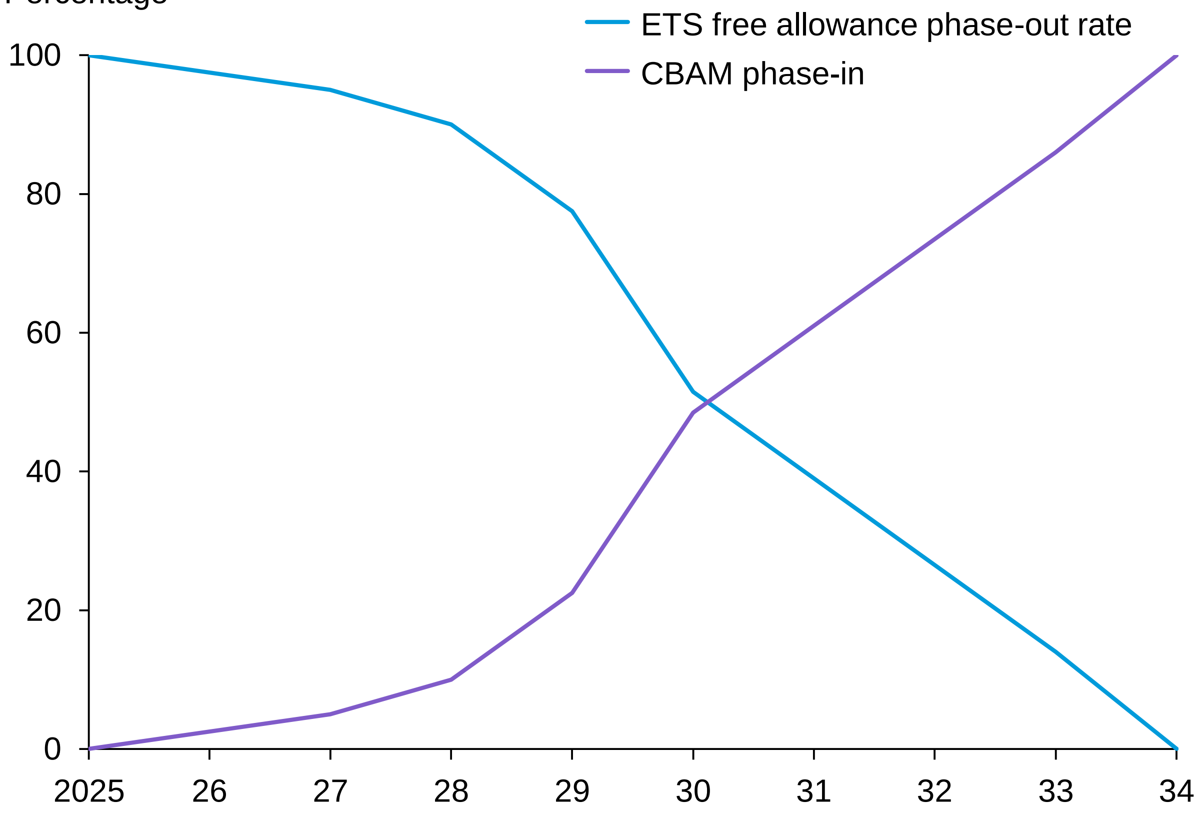
Cement imports to the EU quadrupled between 2016 and 2021

EU cement imports, 2016-21
Mt of cement



CBAM phase-in and ETS free allowance phase-out will start in 2026

CBAM phase-in and ETS free allowances phase-out rate, 2025-34
Percentage



Source: Climate Bonds Initiative (2023)
Credit: Hoshi Ogawa, Sho Tatsuno, Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

US Federal Buy Clean Initiative mandates low-carbon benchmarks for concrete and other construction materials

Clean cement purchase initiative	Material	Emissions benchmark (CO_2e)	Target year	Share of purchases
First Movers Coalition (FMC) – public-private	Cement Concrete	184 kg 70-144 kg	2030	10%
Industrial Deep Decarbonization Initiative (IDDI) – public	Cement	40-125 kg	Various	N/A
ConcreteZero – private	Concrete	100-270 kg	2025	30%
GSA Buy Clean – public	Concrete	242-414 kg	Immediate	100%

Observations

- **The Federal Buy Clean Initiative** focuses on purchasing low-carbon materials like steel and concrete, making up **98%** of federal construction material purchases.
- **Specific low-carbon benchmarks are set**, especially for concrete, to significantly reduce emissions in federal projects.

Sources: The EU Innovation Fund (2024), WRI (2024)

Credit: Hoshi Ogawa, Sho Tatsuno, Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

New York State's Buy Clean Concrete guidelines mandate EPDs and sets GWP limits for concrete

New York State's Buy Clean Concrete guidelines

Section	Explanation
Environmental Standards (EPDs)	• Mandatory Environmental Product Declarations (EPDs) for all concrete mixes starting Jan. 1, 2025. These quantify the environmental impact of products over their life cycle.
Who does this affect?	• State agency projects over $1 million and Department of Transportation projects over $3 million, both of which require significant concrete usage.
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 (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

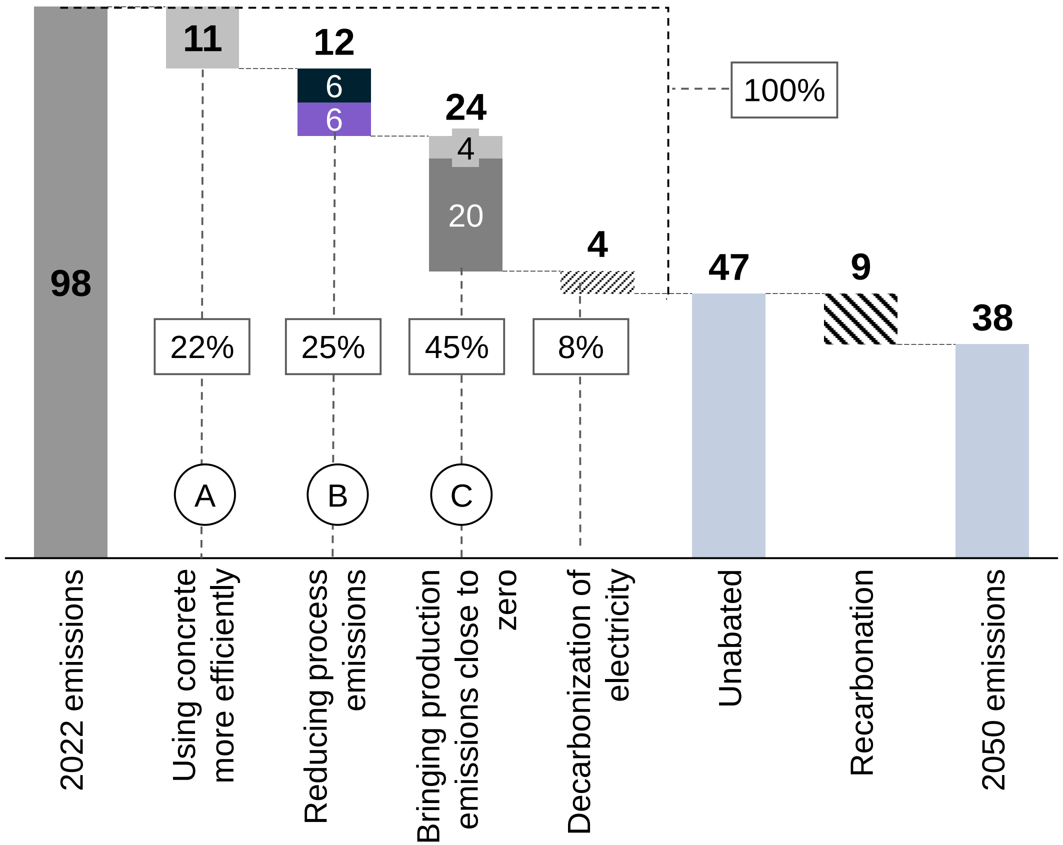
Mission Possible Partnership's 2050 Roadmap envisions improved concrete efficiency, reduced emissions to drive decarbonization

Key decarbonization strategies

Using concrete more efficiently	Reducing process emissions	Minimizing production emissions
• Implementing structural system and design improvements, extending building lifespans, using alternative building materials, and reusing concrete elements to reduce the demand for concrete.	• **Using less clinker per unit of cement**, utilizing less emissions-intensive supplementary cementitious materials (SCMs). • **Using less cement per unit of concrete** by increasing the effective strength of cement and industrializing the concrete production process. • **Bringing alternative low- or zero-carbon chemistries to market** (e.g., alternative binders, decarbonated raw materials).	• **Reducing and eventually eliminating heat emissions** by deploying thermal efficiency measures, replacing fossil fuels with biofuels, hydrogen, or electrification (renewables deployment). • **Capturing remaining process and heat emissions** to store or utilize CCUS.

In addition to these decarbonization levers, concrete reabsorbs carbon dioxide throughout its life cycle through a process called **recarbonation**, which is a carbon sink that could absorb **9 Gt of CO_2 by 2050**, according to estimates.

Cumulative GHG emissions, 2022-50
Gt CO_2



Sources: Mission Possible Partnership (2023), GCCA Concrete Future (2021), IEA Net Zero by 2050 (2021)
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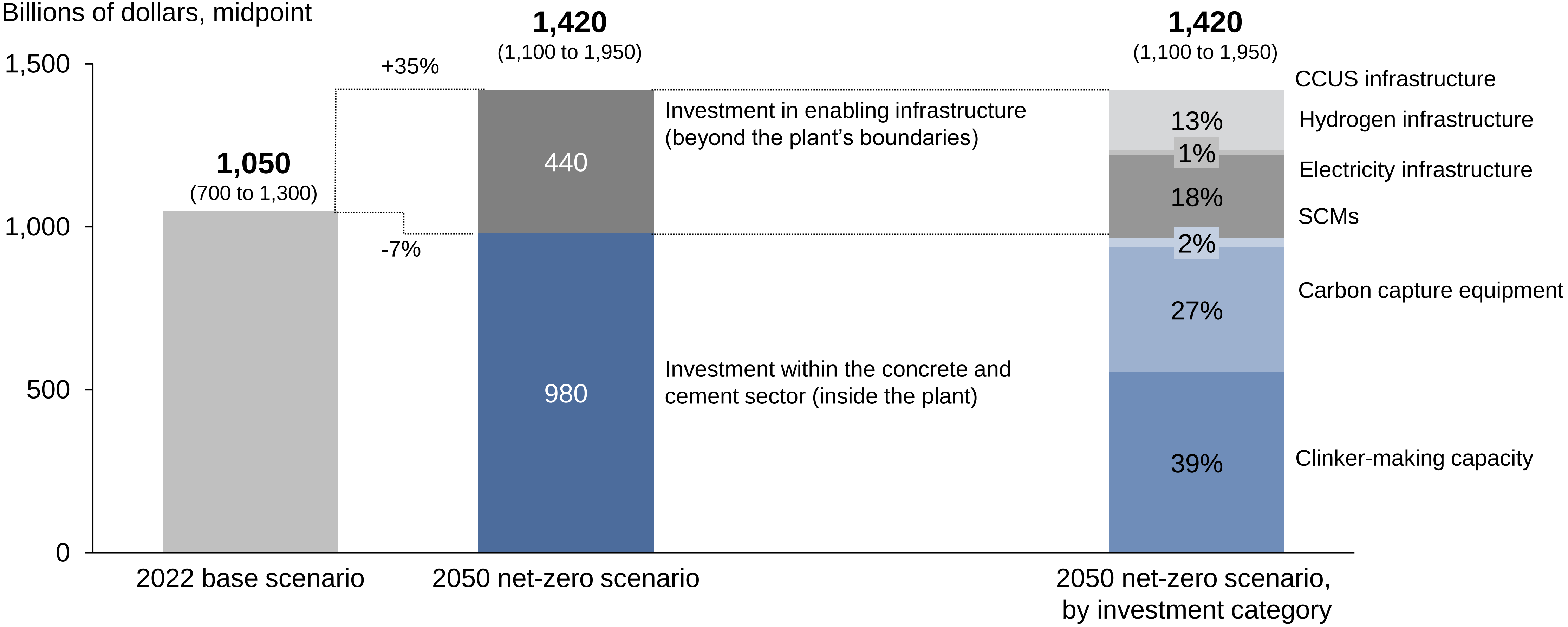
Delivering a net-zero scenario requires a 35% investment increase against a base scenario, due to infrastructure requirements

Cumulative investments, 2022-50
Billions of dollars, midpoint



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

Supply chain stages

Extraction & Raw Materials	Manufacturing	Distribution	Sales & Market Demand	End Use & Application

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)

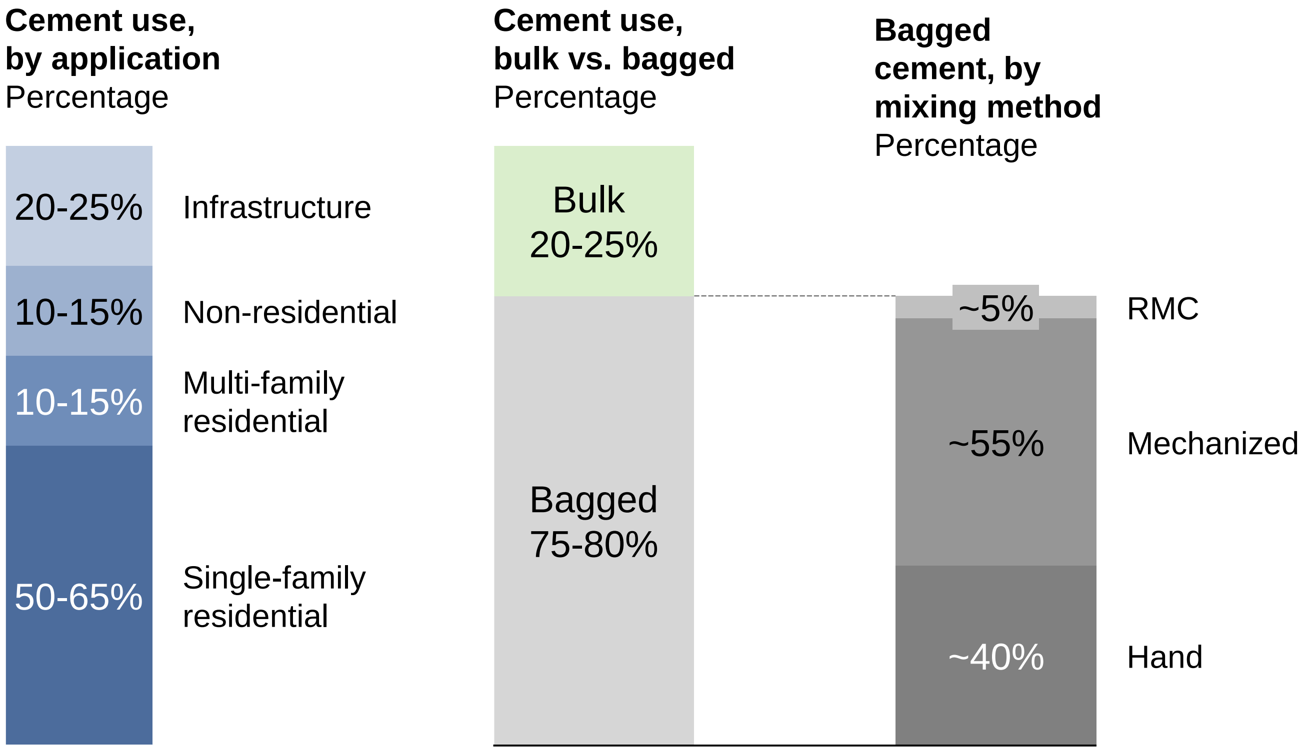
A policy-driven, top-down approach can effectively drive the large-scale adoption of Sublime cement in New York

Leverage existing regulations	Financial incentives	Public-private partnerships	Industry collaboration	Education and training	Stakeholder advocacy
• Utilize New York's **Buy Clean Concrete** guidelines to mandate the use of low-embodied carbon cement in state-funded projects. • Collaborate with state agencies to ensure Sublime cement is listed as an approved material for public procurement.	• Advocate for tax credits, subsidies, and grants for projects using Sublime cement. • Engage with policymakers to create financial incentive programs that reduce the cost burden on construction companies intending to adopt Sublime cement.	• Form alliances with major construction firms and government bodies to pilot large-scale projects using Sublime cement. • Propose collaborative projects where the government supports the initiative with funding and policy backing.	• Partner with industry leaders like Turner Construction to showcase the benefits of Sublime cement in high-profile projects. • Present comprehensive case studies and pilot project results to demonstrate performance and sustainability advantages.	• Conduct workshops and training sessions for architects, engineers, and builders on the benefits and application of Sublime cement. • Implementation: Collaborate with industry associations and educational institutions to reach a wider audience.	• Engage with key stakeholders, including policymakers, environmental groups, and industry leaders, to build support for Sublime cement. • Organize roundtable discussions and forums to discuss the environmental and economic benefits of adopting Sublime cement.

Source: NYS Buy Clean Concrete Guidelines (2023)
Credit: Shailesh Mishra, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

India, the world's second largest cement producer, urgently needs decarbonization strategies to reduce emissions

Snapshot of cement use in India



Observations

India, with 410 million metric tons (FY 2023), is the second largest cement producer globally. Rapid industrialization and urbanization are key drivers of this growth.

Approximately 75 to 80% of cement in India is used for small-scale residential construction, with **40% mixed by hand**. This leads to excessive use and higher emissions.

India is **promoting the use of alternative fuels and raw materials**, such as municipal and agricultural waste, in cement kilns. However, to **further reduce emissions, India should**:

- **Encourage carbon capture and utilization (CCU)** technologies
- **Promote the use of supplementary cementitious materials (SCMs)** like fly ash and slag to reduce clinker content
- **Implement government-led procurement policies** prioritizing lower-carbon concrete
- **Electrify kilns** and explore **hydrogen as a cleaner fuel alternative**
- **Educate** small-scale builders on **efficient cement use** to minimize waste and emissions
- **Revise building codes** to allow and promote the use of blended cements and SCMs, facilitating the adoption of low-carbon solutions

Sources: WEF (2022), Mission Possible Partnership (2023), US Geological Survey (2024)

Credit: Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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Several 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 US 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

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.

Technological uncertainty

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

Stakeholder

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.

Risk-aversion and long adoption cycles

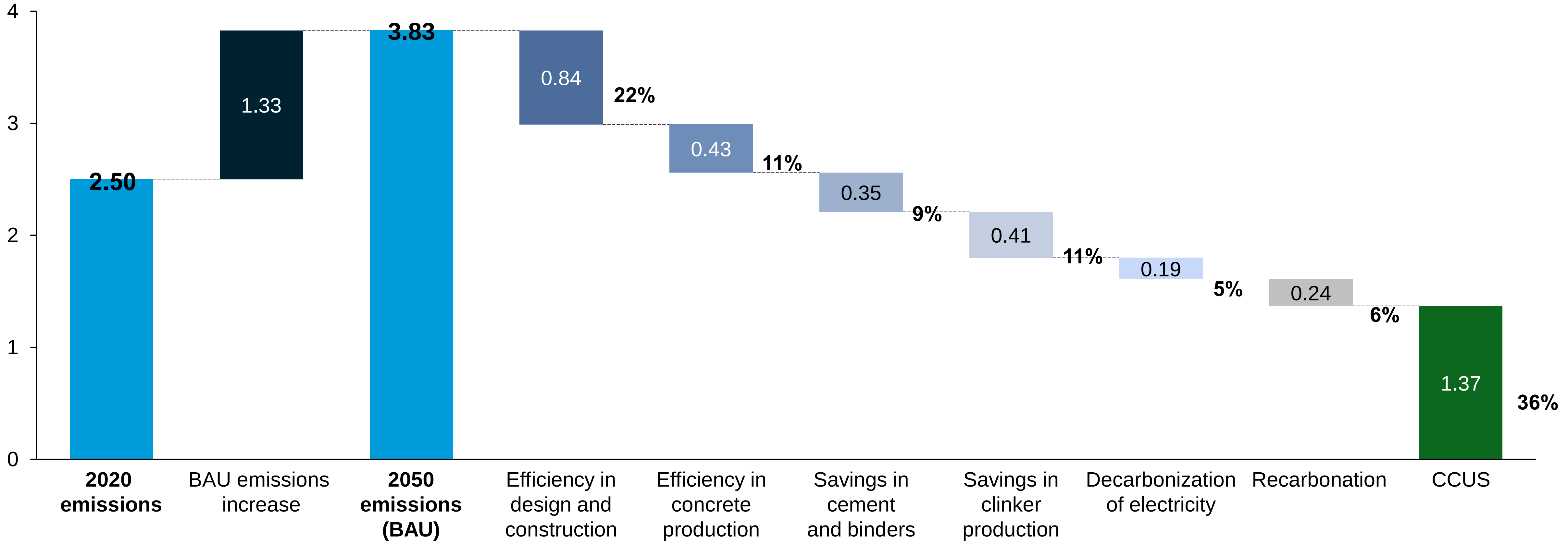
- The cement sector has a **~10- to 20-year adoption cycle** for new blends and materials — both from the **long lead time to update standards** and a **long customer adoption cycle**.
- Contractors, engineers, and ready-mix companies are **risk averse to adopting new technologies** that may lead to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

Source: Department of Energy Liftoff Report (2023)
Credit: Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

GCCA's Net Zero Roadmap presents CCUS and improved material efficiency as the key levers for decarbonizing the cement sector

GCCA decarbonization roadmap, 2020-50

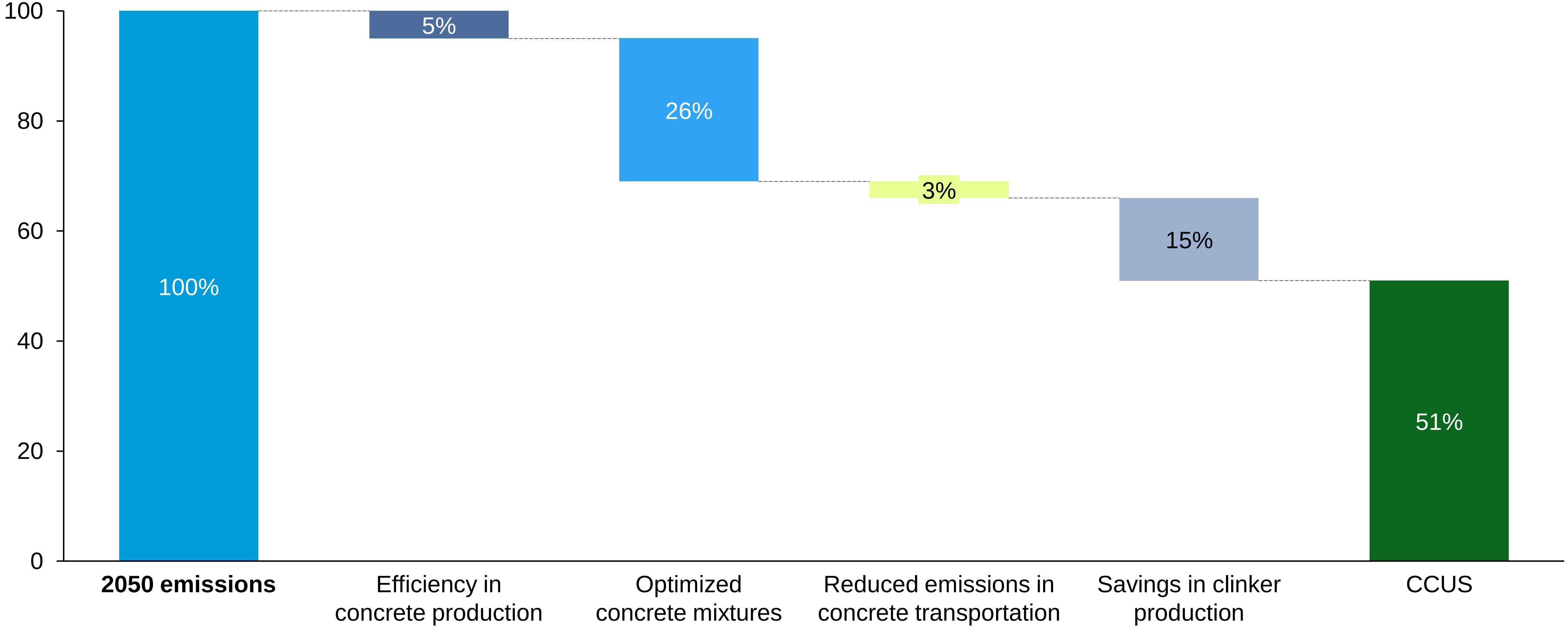
Gt CO_2



Source: GCCA Concrete Future (2021)
Credit: Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

PCA's 2050 Roadmap to Carbon Neutrality: CCUS to abate ~51% of emissions, concrete mixture optimization ~26%

PCA carbon-neutrality levers, 2050
Percentage share of emissions abated

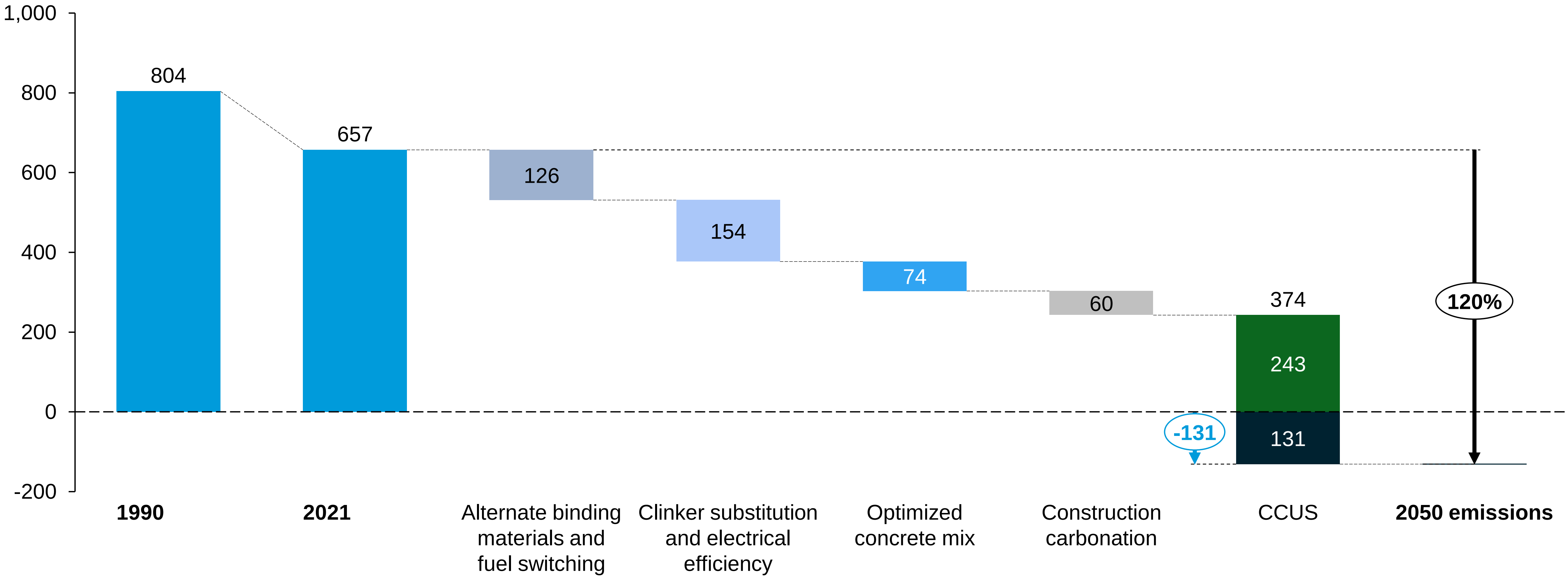


Sources: PCA (2024)
Credit: Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

CEMBUREAU's 2050 roadmap: Achieving -131 kg CO_2/t cement emissions through CCUS, clinker substitution, and circularity

CEMBUREAU emissions including downstream, 1990-2050

kg CO_2 per tonne of cement



Source: CEMBUREAU (2024)

Credit: Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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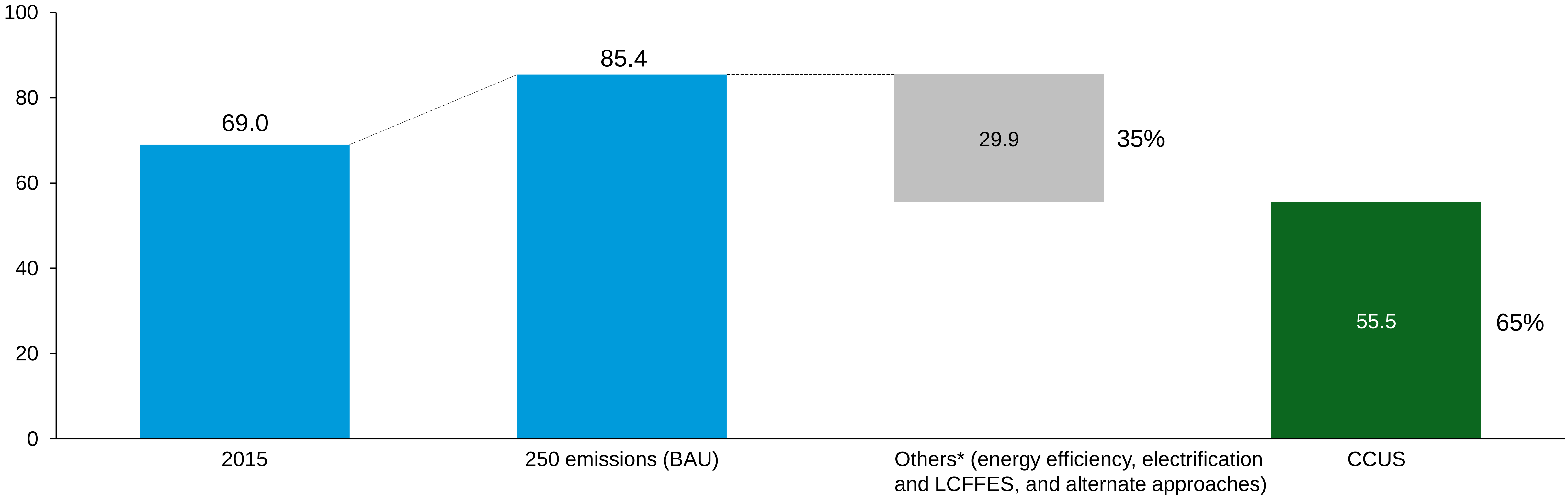
DoE's Industrial Decarbonization Roadmap highlights CCUS as key contributor to 65% of CO_2 emissions reduction for US market

DoE Industrial Decarbonization Roadmap emissions for US cement manufacturing sector, 2015-50
Mt CO_2



Note: *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 (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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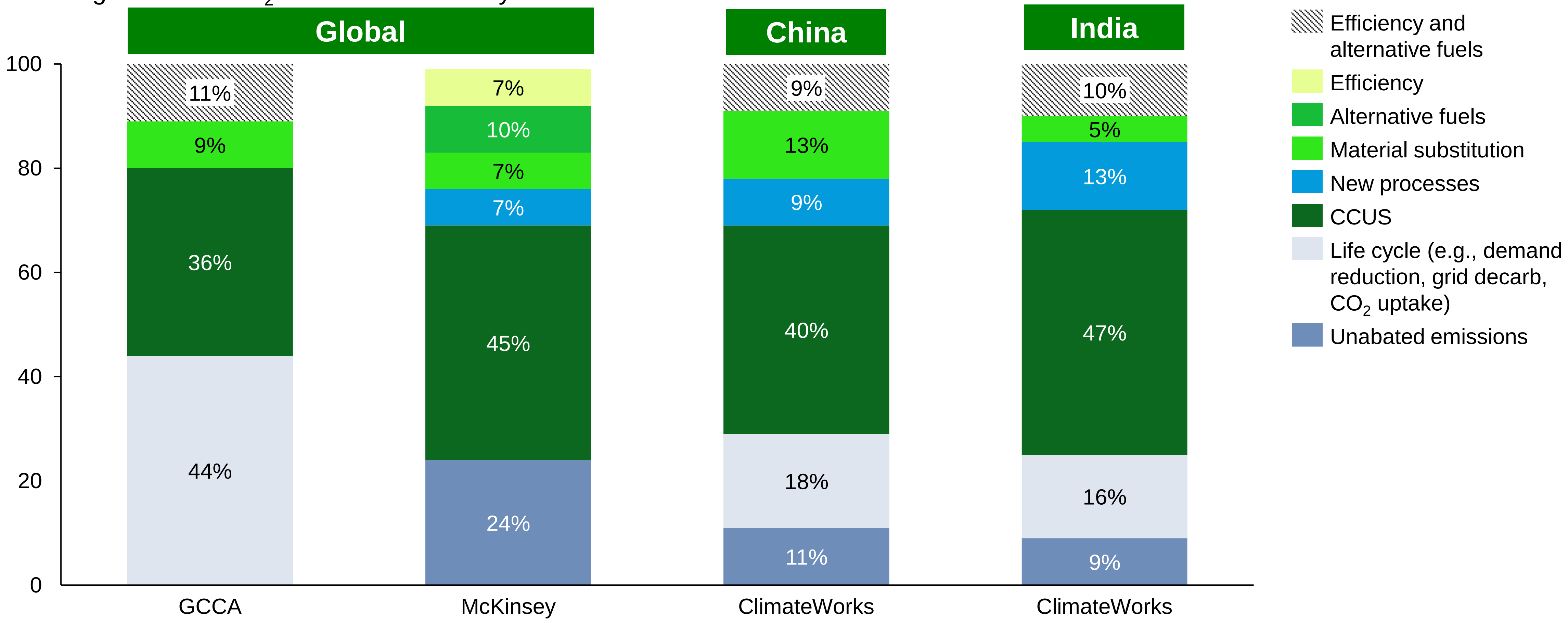
New technologies key to decarbonization: CCUS abate ~35-50% emissions; new methods and material substitution ~5-15% each

Comparison of international decarbonization pathways, 2050

Percentage share of CO_2 emissions abated by measures



Sources: DoE Pathways to Commercial Liftoff (2023), GCCA Concrete Future (2021), McKinsey (2020), ClimateWorks Foundation (2021)

Credit: Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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The DoE's four-track pathway primarily hinges on currently deployable measures and alternative production methods

Low-carbon cement: Four-track pathway to liftoff

Technology track		Pathway to commercial liftoff		Abatement potential by 2050	Notes
A **Currently deployable measures**	• Clinker substitution • Energy efficiency • Alternative fuels	Rapid deployment, incentivized by demand signal from large buyers and enabled by accelerated validation of low-carbon blends		~ 30-40%	Numerical value for total emissions and abatement share from each lever is not available.
B **CCUS**	• CCUS retrofits and integration into new-build plants	Initial ~3-5 demonstrations enabled by 45Q and government support	Accelerate buildout of CCUS, enabled by 45Q, cost reductions, and coordinated procurement to create investable demand signal	~ 60-70%	
C **Alternative production methods**	• Alternative feedstocks • Electrochemical reactions	Initial ~3-5 greenfield demonstration plants enabled by government support	Accelerate buildout of greenfield plants, enabled by cost reductions and coordinated procurement to create investable demand signal		
D **Alternative binder chemistries**	• Alternative chemistries to traditional clinkers	- Initial market share in non-structural niches - Testing and validation, updated standards, and market education to enable wider deployment - Expansion of supply chain to meet growing demand	- Liftoff achieved in broader market - Potential to pull forward timeline with expanded use of performance-based standards		

Source: DoE Pathways to Commercial Liftoff (2023)

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Decarbonization roadmaps: 2050 abatement projections

Levers	GCCA	MPP	PCA	CEMB	Notes
Efficiency in design and construction	22%	22%	-		PCA: 30% construction efficiency, emission reduction not specified (P41)
Efficiency in concrete production	11%	12.5%	5%		PCA: 5% of total CO_2 footprint for concrete from production, can be totally avoided by 2050 (P39)
Optimized concrete mixtures	-	-	26%	11%	PCA: CO_2 footprint avoided ~26% by 2050 (P39)
Concrete transportation	-	-	3%		PCA: Total CO_2 footprint of concrete transportation, can be reduced by 3% by 2050 (P39)
Savings in cement and binders	9%	12.5%	-	19%	PCA: Mentions increased use of decarbonated raw materials but doesn't specify the emission abatement percentage (P27) CEMB: Alternate binding materials and fuel switching
Savings in clinker production	11%	-	15%	24%	PCA notes 15% savings in clinker and equivalent reduction in CO_2 emissions (P33) via increased SCMs ~5 to 20% by 2050 CEMB: Clinker substitution and electrical efficiency
Decarbonization of electricity	5%	8%	-		
Switching to alternative fuels and energy efficiency	-	7%	-		
Carbon capture, utilization, and storage (CCUS)	36%	38%	51%	57%	
CO_2 sink: Recarbonation	6%	-	-	9%	CEMB: Construction carbonation
	100%	**100%**	**100%**	**120%**	

The DoE projects that currently deployable measures can abate ~30-40% of emissions by 2050; the remaining ~60-70% will require alternative production methods, alternative binder chemistries, and CCUS technologies

CEMBUREAU's pathway projected a 120% reduction in 2021 emissions, achieving -131 kg CO_2/t cement emissions by 2050

Sources: GCCA Concrete Future (2021), Mission Possible Partnership (2023), PCA (2024), DoE Pathways to Commercial Liftoff (2023)

Credit: Shailesh Mishra, Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Decarbonizing cement and concrete requires economic and regulatory levers in addition to voluntary measures

Carbon accounting and trading

Integrating financial incentives with regulatory compliance, carbon accounting and trading drives investment and innovation toward decarbonization.

Tax credits and subsidies

Tax credits and subsidies reduce companies' financial barriers to adopting low-carbon innovations.

Direct government funding

Directly funding research, development, and infrastructure needed for low-carbon technology adoptions can accelerate decarbonization.

Green public procurement (GPP)

By defining and implementing GPP practices, governments can lead the way for the private sector to leverage the tools, methodologies, and standards set.

Performance-based standards

Performance-based standards in place of recipe-based standards enable novel production methods to enter the market.

Contracts for difference (CFDs)

CFDs could boost investment in green cement production by tying incentives to environmental targets, encouraging capital flow into sustainable projects.

Securitization

Securitization of green cement projects into tradable financial instruments enables access to capital by offering attractive investment opportunities while spreading risk among investors.

Pass-through certificates (PTC)

By enabling cement manufacturers to earn and trade certificates based on verified emissions reductions, PTCs attract investors seeking to offset their emissions.

Sources: DoE Liftoff Report (2023), WRI (2024), Columbia Center for Sustainable Investment (2024), Climate Bonds Initiative (2023)
Credit: Isabel Hoyos, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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Appendix

The top 10 cement producers make up ~44% of total global cement production capacity of ~4 billion tonnes annually

Top 10 cement producers

Company	Established	Headquarters	Cement capacity (Mt per year)	Sales volumes (Mt)	Cement revenues (in US billions of dollars)
China National Building Material (CNBM)	1984	Beijing, China	530	127 (6-month 2023)	5.38 (6-month 2023)
Anhui Conch Cement	1997	Wuhan, China	388	134 (6-month 2023)	6.46 (6-month 2023)
Holcim	1912	Zug, Switzerland	274	N/A	11.5 (6-month 2023)
Heidelberg Materials	1874	Heidelberg, Germany	185.7	N/A	17.3 (9-month 2023)
China Resources Building Materials Technology	2003	Hong Kong, China	91.8	56.7 (6-month 2023)	N/A
Cemex	1906	San Pedro, Mexico	83.6	39.1 (9-month 2023)	13.2 (9-month 2023)
UltraTech Cement	1983	Mumbai, India	78.9	56.7 (6-month FY24)	N/A
Votorantim Cimentos	1933	Sao Paulo, Brazil	70	27.7 (9-month 2023)	N/A
Taiwan Cement Corporation	1946	Taipei, Taiwan	65.9	N/A	2.6 (9-month 2023)
Sinoma	2003	Beijing, China	58.3	N/A	N/A

Source: Global Cement Magazine (2024)
Credit: Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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Several startups have developed disruptive alternative technology creating cement and concrete alternatives

Company	Established	Headquarters	Total funding	Category
Brimstone	2019	Oakland, CA, US	$60M	Silicate alternatives
Terra CO_2	2012	Golden, CO, US	$81.4M	Silicate alternatives
Solidia Technologies	2008	Piscataway, NJ, US	$145M	Silicate alternatives
CemVision	2020	Stockholm, Sweden	€2.1M	Chemical/slag alternatives
Material Evolution	2017	Teesside, UK	£15M	Chemical/slag alternatives
CarbiCrete	2016	Lachine, Canada	$27.6M	Chemical/slag alternatives
Biomason	2012	Durham, NC, US	$95M	Bio alternatives
Sublime Systems	2020	Somerville, MA, US	$45.9M	Process optimization
Alcemy	2018	Berlin, Germany	€13M	Process optimization
CarbonCure	2007	Dartmouth, Canada	$92.4M	Carbon cured concrete

Source: Crunchbase (2024)

Credit: Hoshi Ogawa, Sho Tatsuno, Jessica Cong, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

Model assumptions for Track A in the DoE's Liftoff report — clinker substitution, alternative fuels, and efficiency measures

Scenario outputs	**2030: Moderate deployment**		**2030: Aggressive deployment**		**2050**	
Levers	**Abatement potential (Mt CO_2)**	**% of BAU emissions abated**	**Abatement potential (Mt CO_2)**	**% of BAU emissions abated**	**Abatement potential (Mt CO_2)**	**% of BAU emissions abated**
Energy efficiency	1.5	2%	1.5	2%	6.7	7%
Alternative fuels – biomass	0.6	1%	3.4	4%	4.5	5%
Alternative fuels – waste	6.4	7%	6.4	7%	10.1	10%
Clinker substitution	11.4	13%	19.7	23%	26.0	27%
Total	**19.9**	**23%**	**31**	**36%**	**47.3**	**49%**

Source: DoE Pathways to Commercial Liftoff (2023)
Credit: Shailesh Mishra, Hyae Ryung Kim, and Gernot Wagner (17 September 2024); share/adapt with attribution. Contact: gwagner@columbia.edu

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
GSA	General Services Administration
Gt	Gigatonne (billion metric tonnes)
GWP	Global warming potential
H_2	Hydrogen
H_2O	Water
IDDI	Industrial Deep Decarbonization Initiative
IEA	International Energy Agency
IRA	Inflation Reduction Act
LCA	Life Cycle Assessment
Mt	Megatonne (million metric tonnes)
MTPA	Million tonnes 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
US	United States