Economics of Decarbonizing Cement

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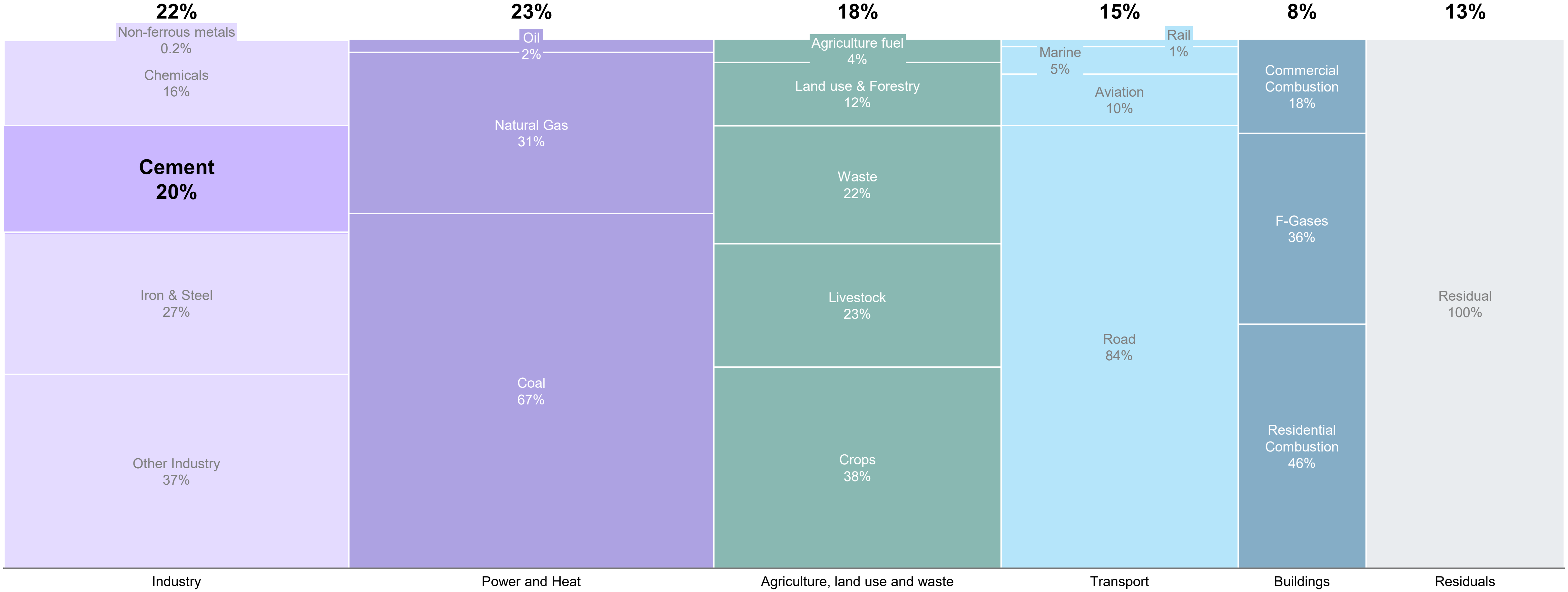
Cement and concrete production account for ~5 to 8% of global CO_2 emissions, mostly scope 1

CO_2e emissions in 2025: ~55 billion tonnes



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” (8 May 2026).

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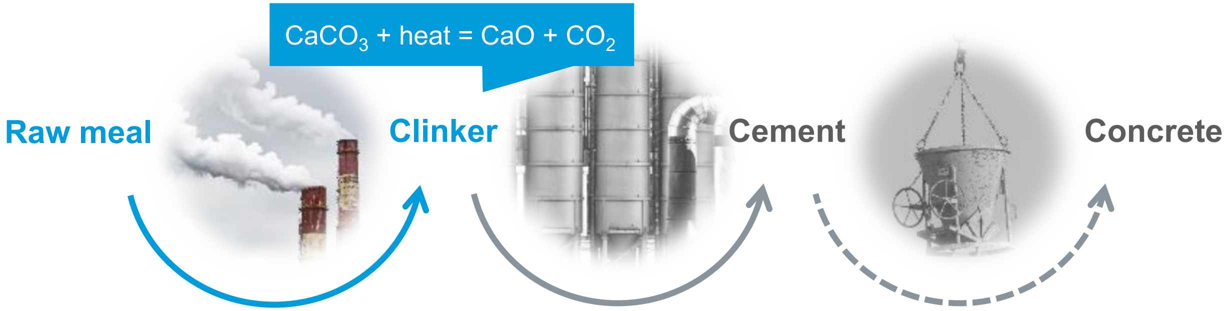
Clinker production accounts for ~85% of cement emissions; dry kiln adoption has led to significant efficiency gains

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

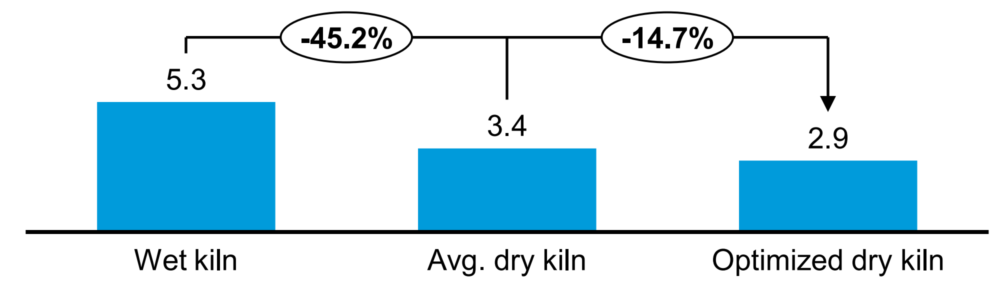
- Limestone is partially decomposed into lime in a combustion chamber before entering the kiln.

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/ton 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.

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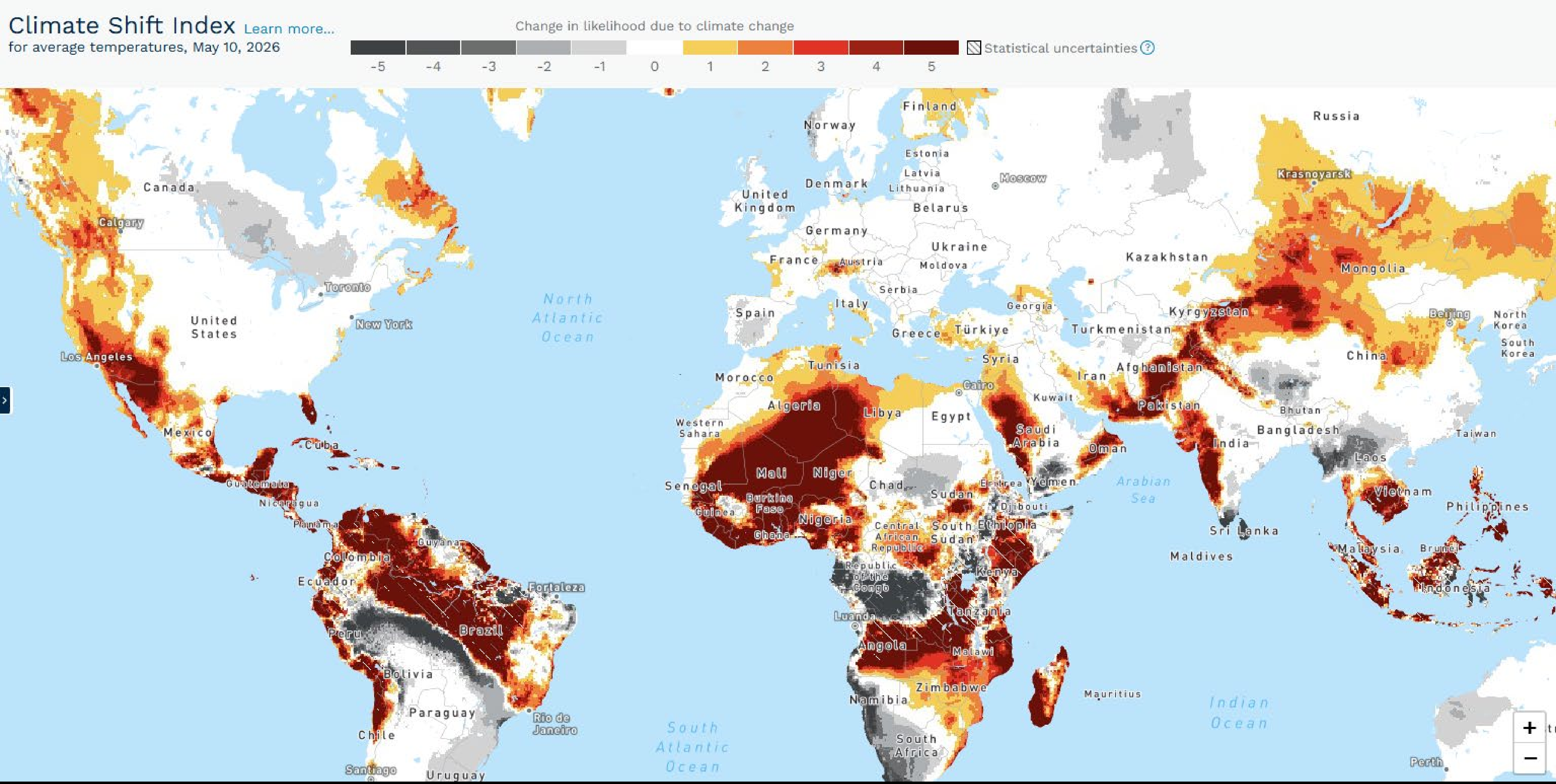
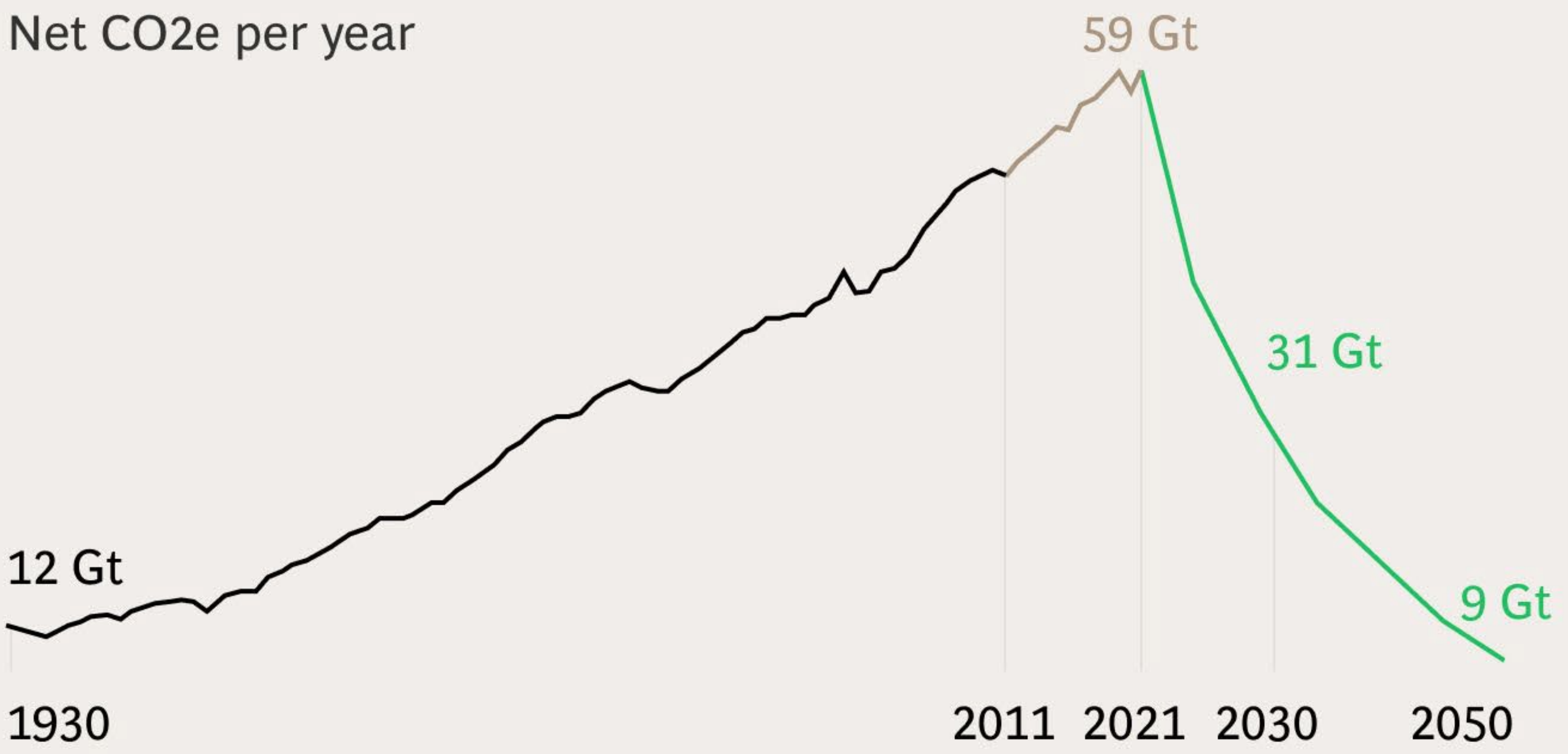


Climate Shift Index Learn more...

for average temperatures, May 10, 2026

Source: climatecentral.org/climate-shift-index

Major course correction needed to achieve the 1.5°C ambition



-7%
annual reduction in emissions needed by 2030 to meet the 1.5°C pathway

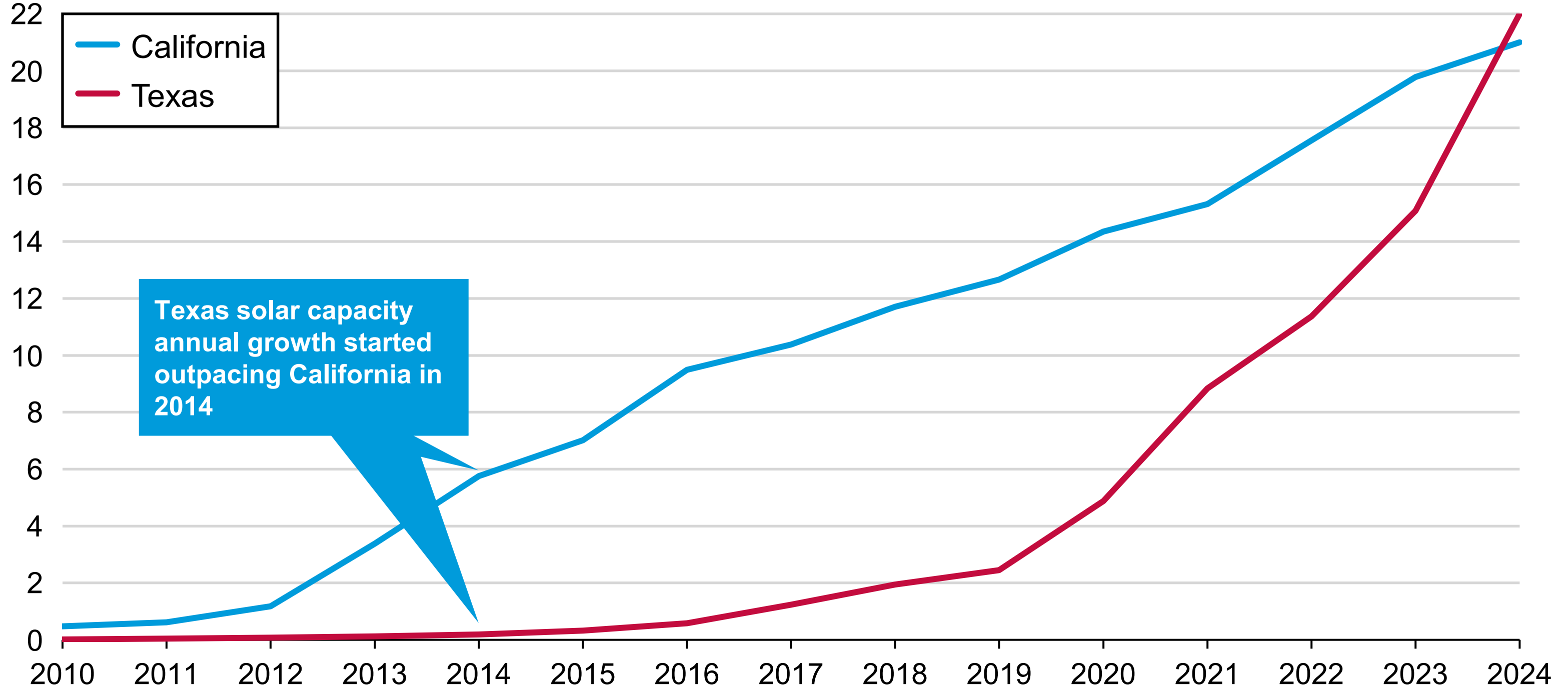
+1.5%
recent annual increase in emissions from 2011-2021

Sources: IPCC, PIK, BCG analysis

Deregulated Texas energy market boon for solar, surpassing California in 2024

Total installed utility-scale solar capacity in Texas and California, *GW*

CAGR '10-'15	**CAGR '15-'20**	**CAGR '20-'24**
CA: 71%	CA: 15%	CA: 10%
TX: 87%	TX: 73%	TX: 46%



Texas solar capacity annual growth started outpacing California in 2014

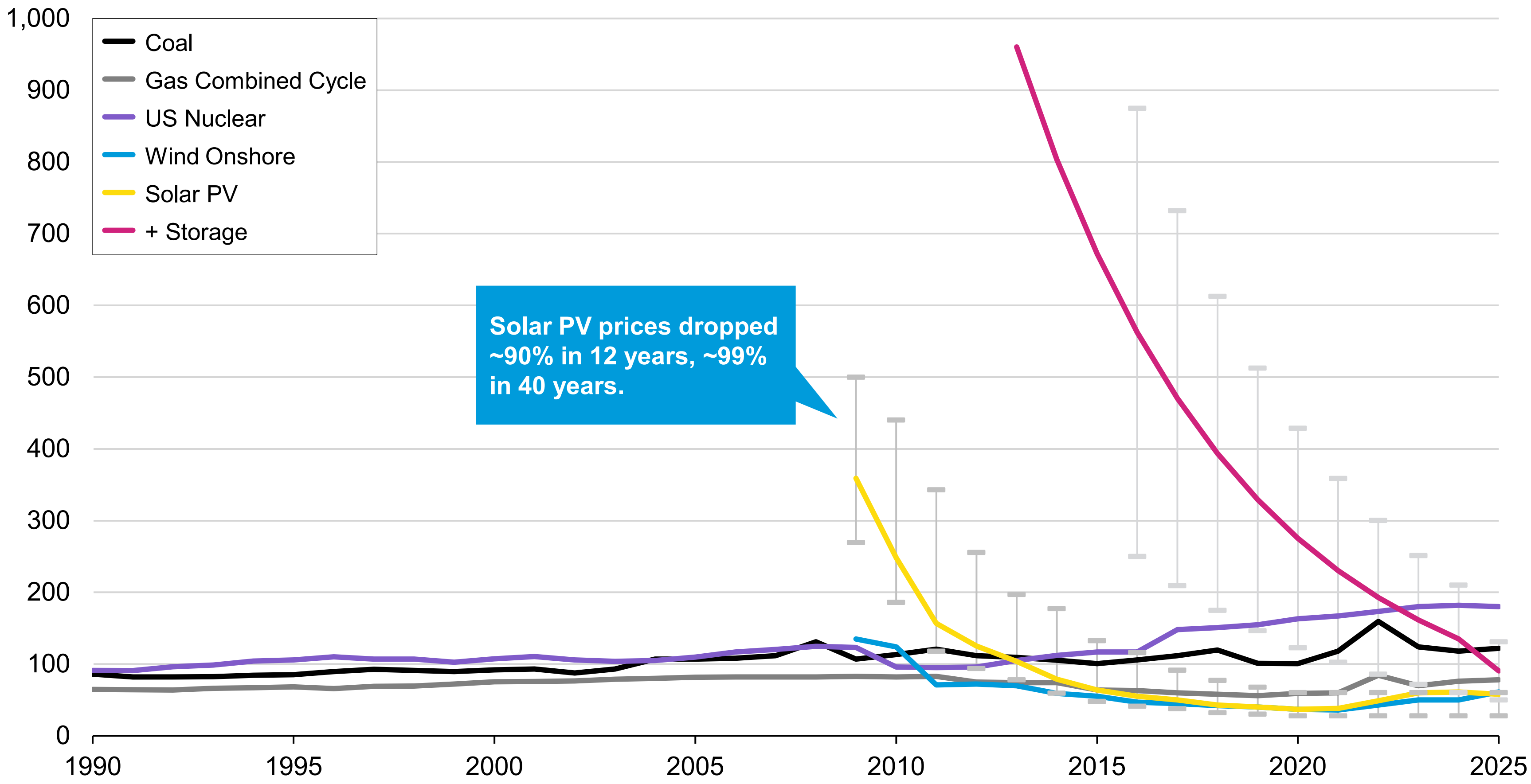
Observations

- **Texas surpassed California** as leading solar PV state after **adding 1.6 GW in Q2 of 2024** (ACP).
- Texas installed nearly **9 GW of new solar by the end of 2024** – over one-fourth of the U.S. 2024 additions – for a **total capacity of 27.5 GW** (ACP).
- Texas is **expected to install 11.6 GW** new utility-scale solar in 2025 (EIA).
- **Texas' advantage:**
  - ⊕ Deregulated, electricity-only energy market
  - ⊕ Streamlined approval process
  - ⊕ Abundant land
  - ⊖ Minimal state-incentives
- **California's challenge**:
  - ⊕ Strong state incentives
  - ⊖ Strict regulations
  - ⊖ Interconnection delays

Source: ACP, Clean Power in 2024 (2025); EIA, Solar, battery storage to lead new U.S. generating capacity additions in 2025 (2025).
Credit: Hyae Ryung Kim, Taicheng Jin, Isabel Hoyos, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (20 March 2025).

Utility-scale solar and wind now cheaper than fossil fuels, battery storage costs not far behind and falling fast

Levelized cost of electricity (LCOE) & storage (LCOS) ($USD/MWh)



Solar PV prices dropped ~90% in 12 years, ~99% in 40 years.

Observations

- **Solar photovoltaic (PV) prices dropped by ~80% in the past decade,** wind by ~70%, and lithium-ion battery costs by ~90%.
  - PV price drop primarily driven by **improvements in module efficiency** and **economies of scale.**
  - **Onshore wind** remained the cheapest for the longest, **now beaten by PV**.
- **Gas combined cycle** power plants **cheaper than coal**, more expensive than both solar and wind.
  - Rapid scale-up of utility-scale batteries "killer app" to replace gas on grid.
  - **Battery prices expected to continue falling** due to cell manufacturing overcapacity, economies of scale, and switch to lower-cost lithium-iron-phosphate (LFP) batteries.

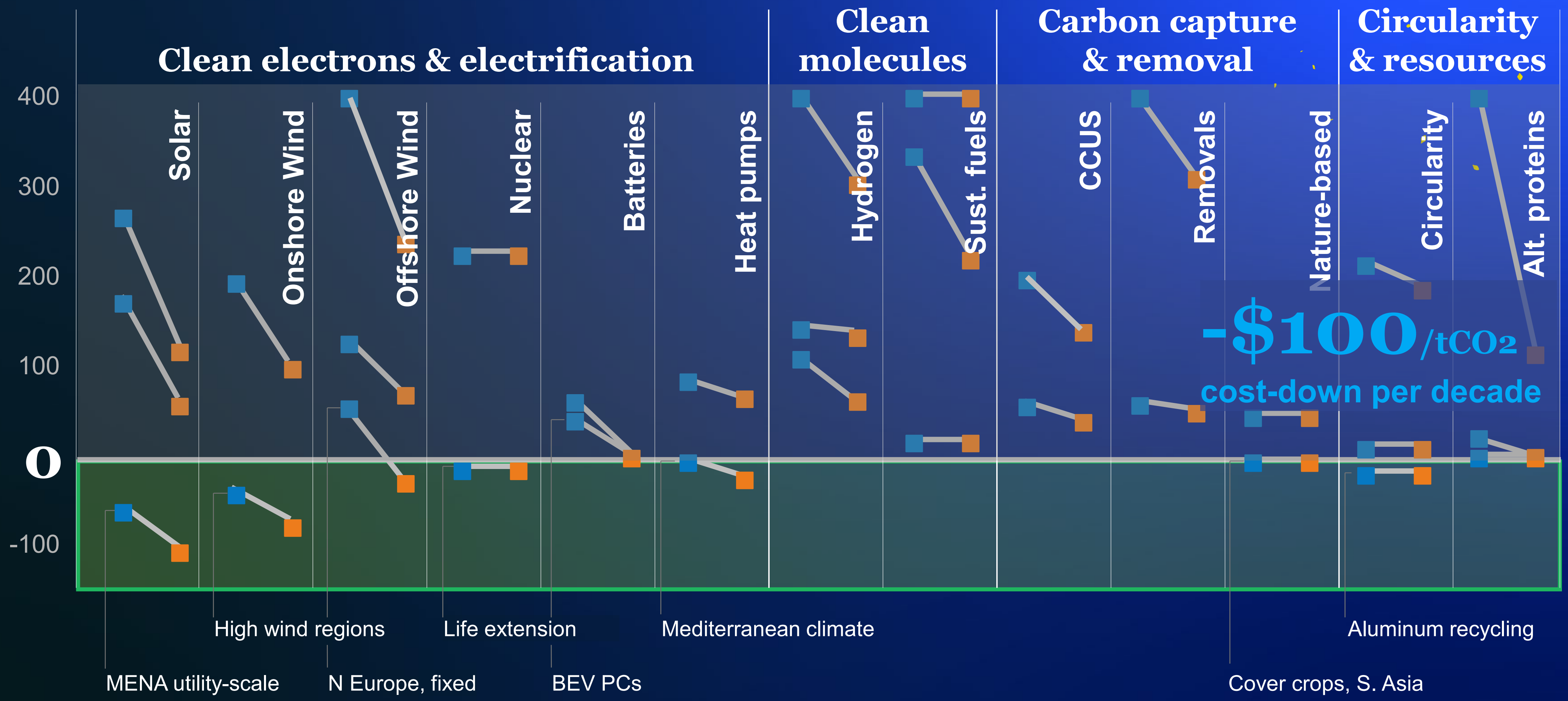
Sources: Lazard, LCOE+ (2025); Our World in Data, Our World in Data (2024); Energy Institute, Statistical Review of World Energy (2024); BNEF, Battery Price Survey (2024); Kavlak *et al.*, Evaluating the Causes of Cost Reduction in Photovoltaic Modules (2018).

Credit: Hyae Ryung Kim, Xiaodan Zhu, and Gernot Wagner. Share with attribution: Kim *et al.*, "Scaling Solar" (14 August 2025).

Bernd Heid, Senior Partner, McKinsey, at Columbia Business School

10 % of techs in the money today – steep cost-down to 2030

Estimated abatement costs, USD/tCO_2e



Source: McKinsey Global MACC with regional/product estimations

McKinsey & Company

100$/tCO$_2$ carbon tax would make most techs competitive

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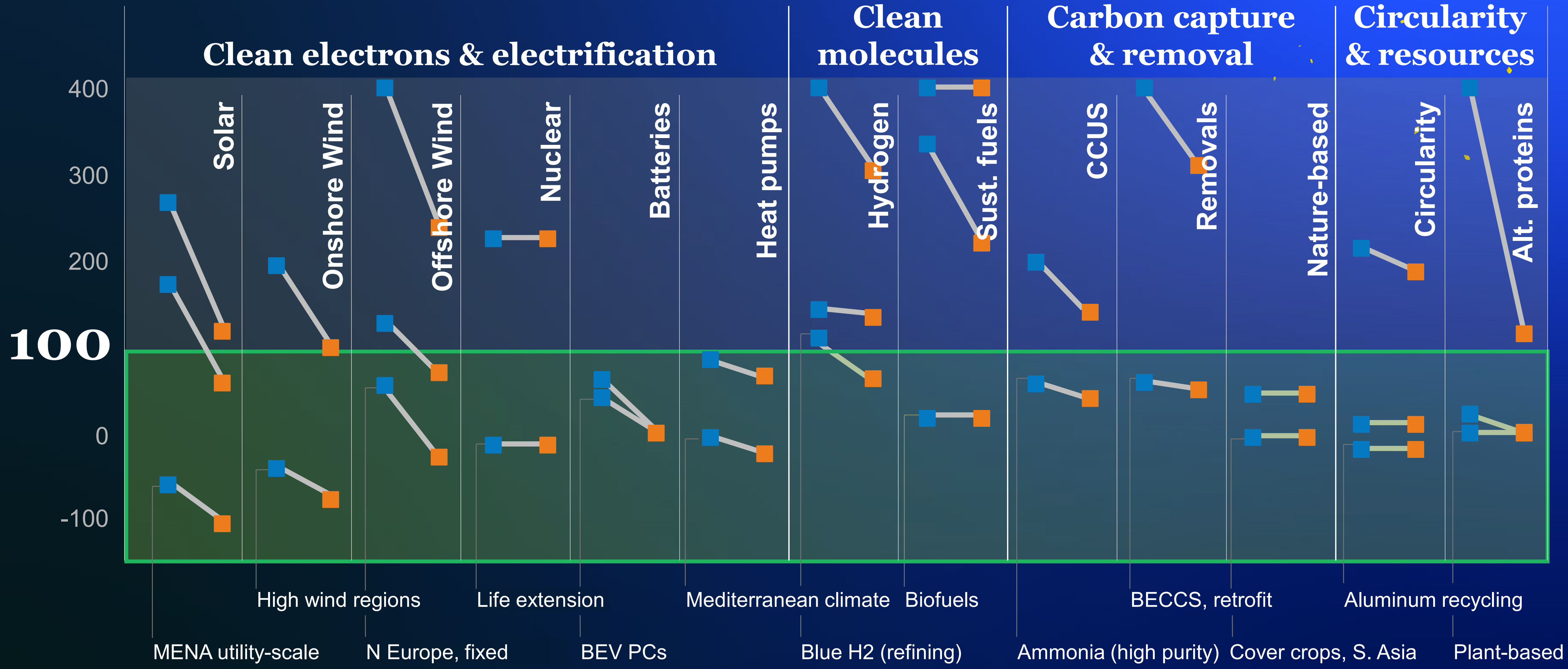

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McKinsey & Company

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. • SCMs 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, 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, $\$/\text{tCO}_2\text{e}$	-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)

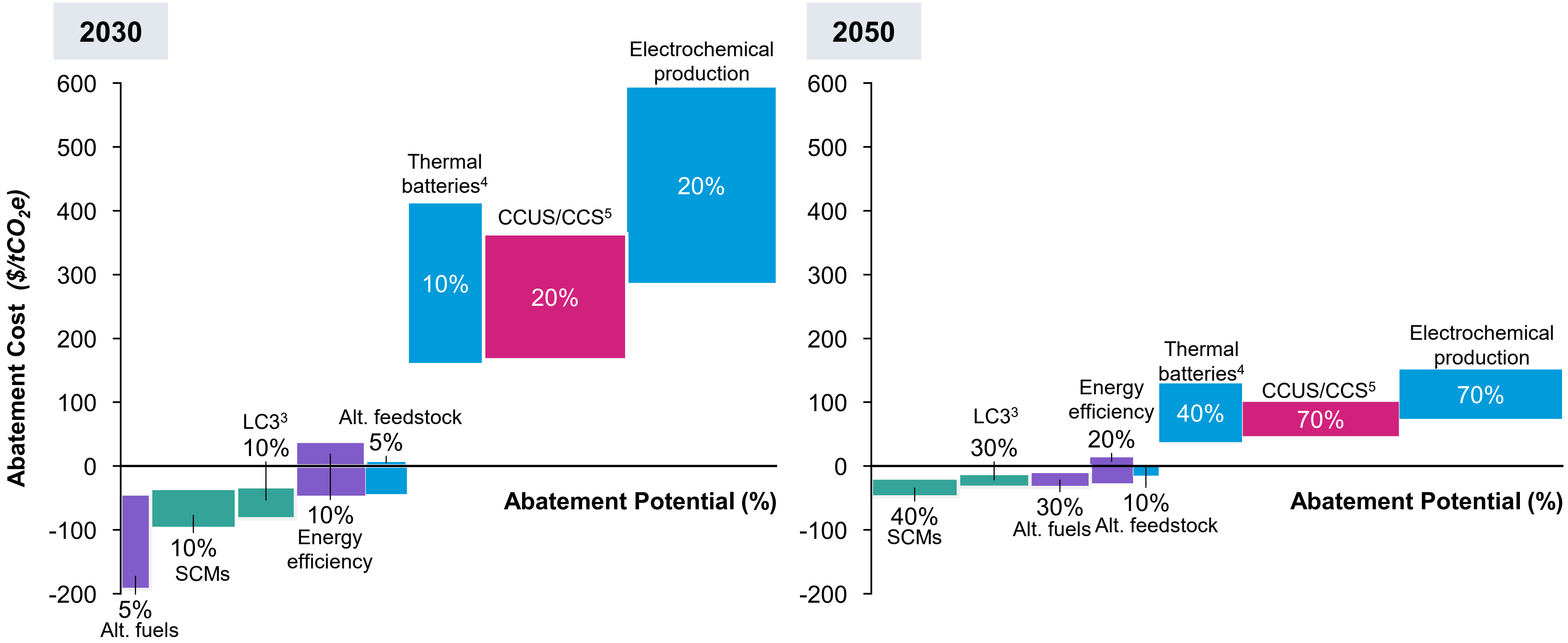
[1] Unconstrained theoretical abatement potential for a given tonne of cement produced for each approach in isolation. [2] Assumes clean energy source. [3] Abatement cost of emerging technologies is based on estimates and has high uncertainty. [4] Reflects the approximate emissions gap after other measures, 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, 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” (8 May 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.**

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❶ Not if, *when*

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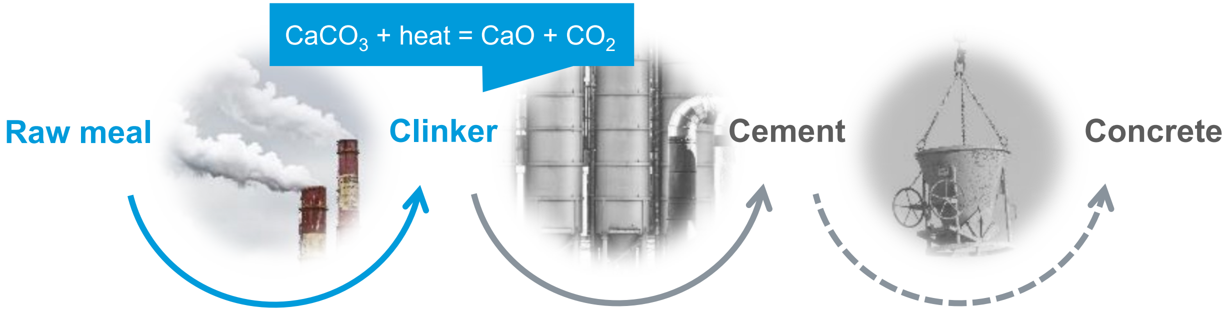

1 Preheat

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- 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

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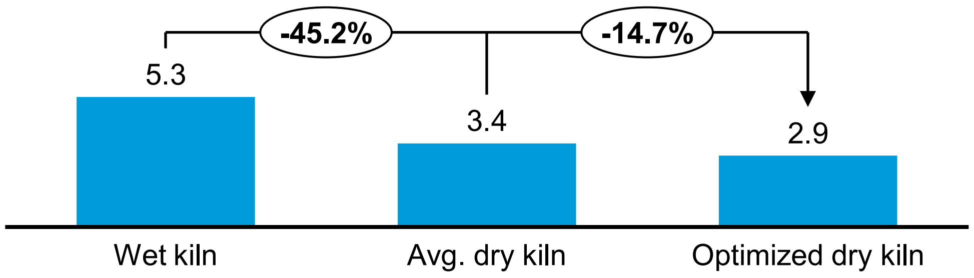

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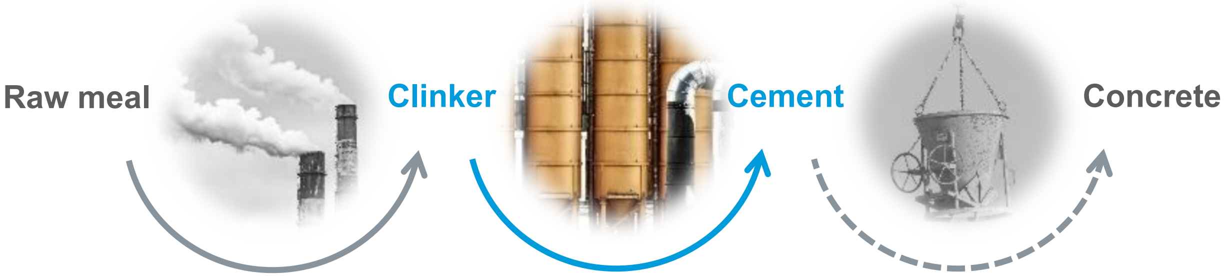
Clinker production produces ~85% cement emissions; lowering clinker-to-cement ratio can drive marginal emissions reductions

Clinker-to-cement production process[1]



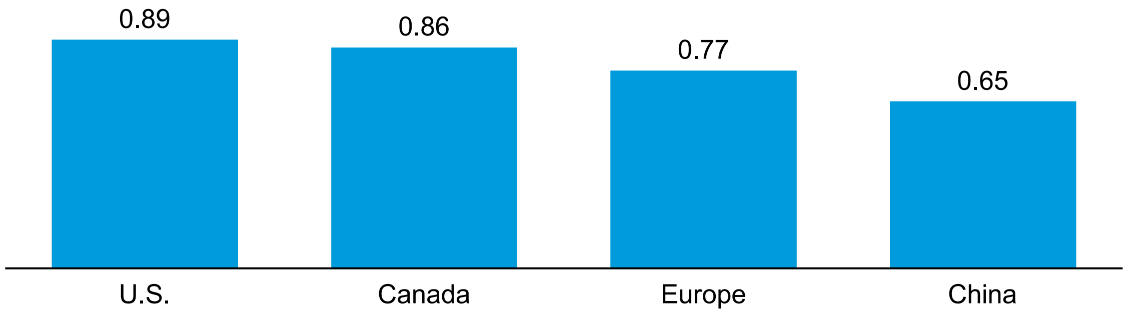
① Cooling

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

② Grinding and blending

- Clinker is mixed with 4-5% 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.

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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).

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❶ Not if, *when*

❷ Innovator’s Dilemma

Wagner, “Who pays for cutting carbon out of making cement?” (*Financial Times*, 19 May 2025)

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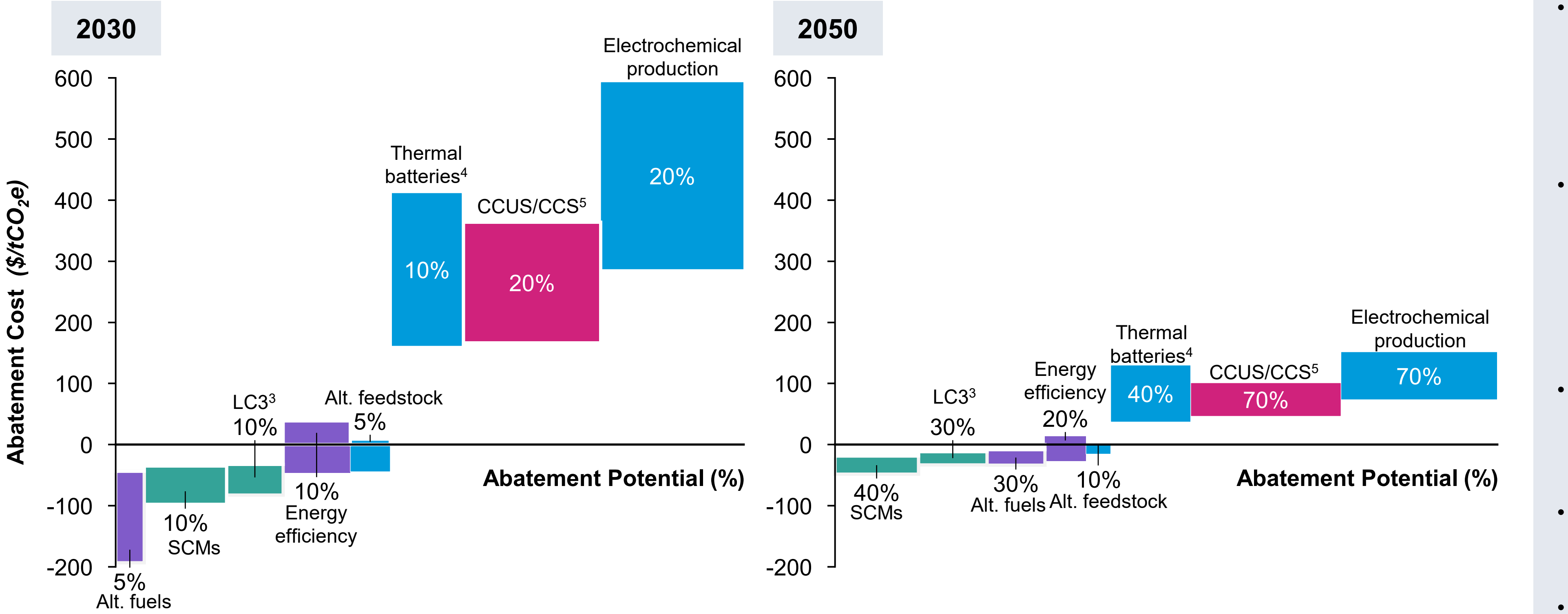

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① **Not if, *when***

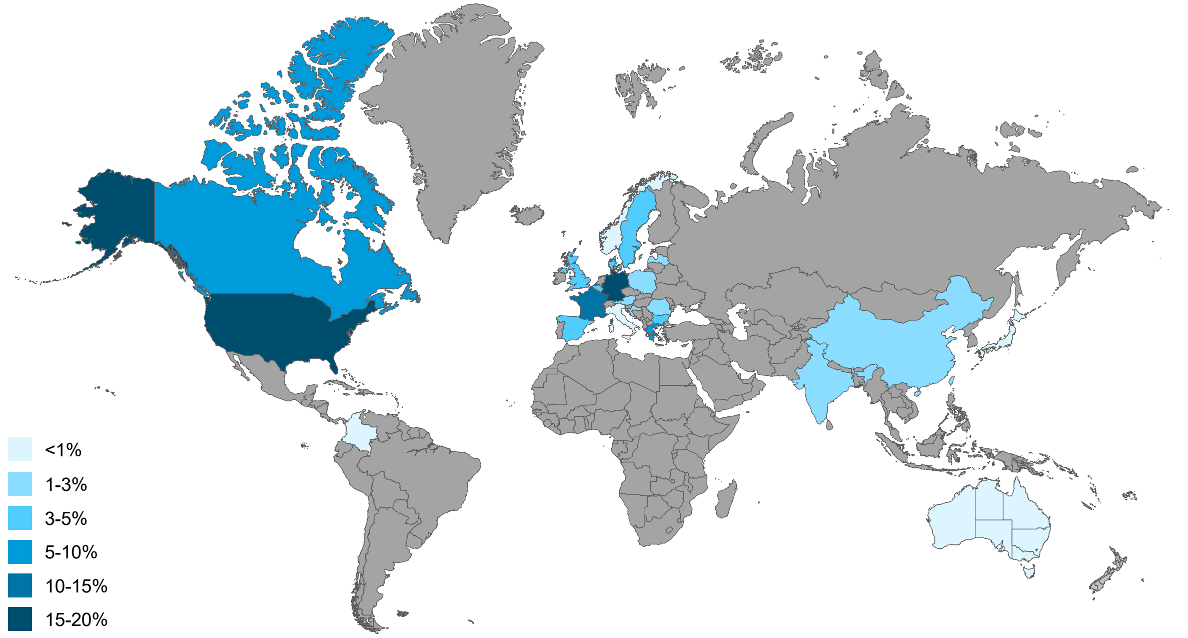
② **Innovator’s Dilemma**

③ **Who pays?**

Wagner, “Who pays for cutting carbon out of making cement?” (*Financial Times*, 19 May 2025)

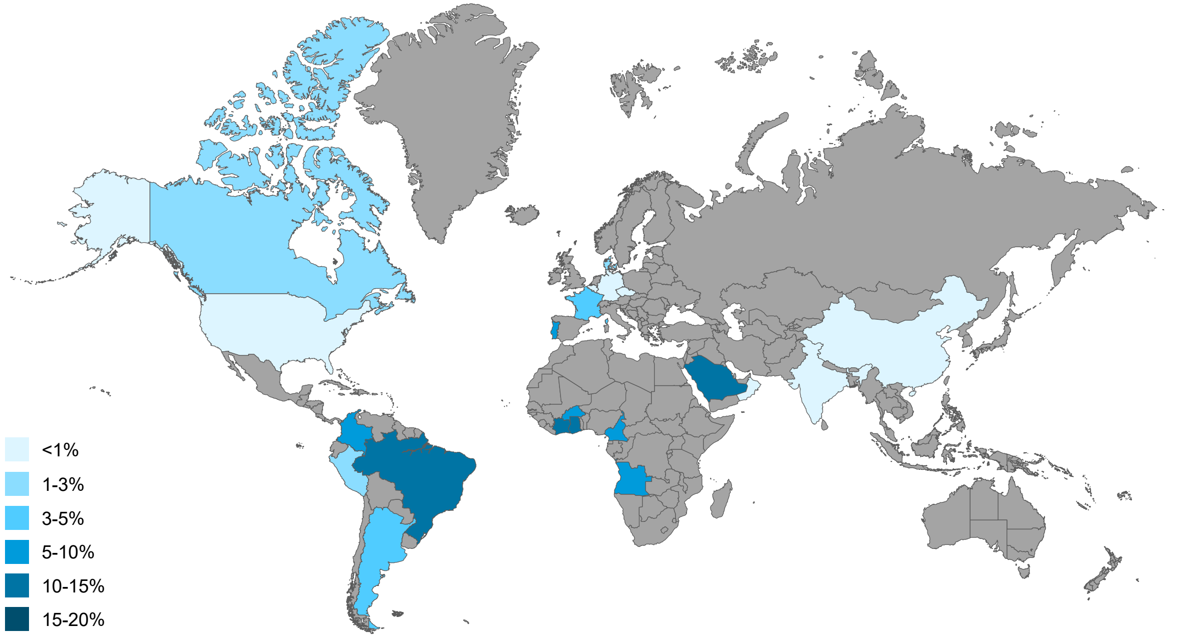
Investment capacity and infrastructure drive CCUS in Global North; clay reserves and capital constraints drive LC3 in South

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" (8 May 2026).

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High capex and long horizons mean climate hard-tech startups must overcome technological and commercial “Valleys of Death”

Overcoming the first “Valley of Death” 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 lay-out	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 + 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 as 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)
- Elaborate development and testing process with high capital costs due to the hard-tech character of climate start-ups
- Capital scales ~5–10x 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 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 obtain investments

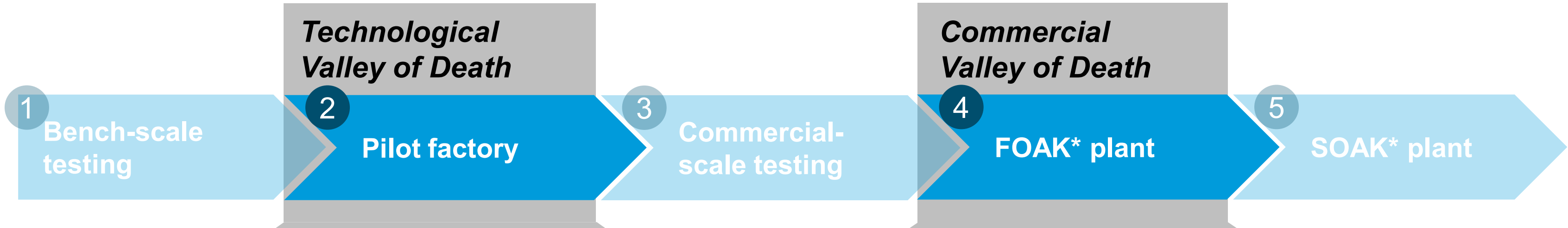
[1]FOAK = First Of A Kind; SOAK = Second Of A Kind; [2]Capital costs refer to construction CAPEX only; excludes OPEX, financing costs, and pre-FID development expenditure

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” (8 May 2026).

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

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



Technological Valley of Death

Commercial Valley of Death

1 Bench-scale testing

2 Pilot factory

3 Commercial-scale testing

4 FOAK* plant

5 SOAK* plant

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

- **Offtake agreements**, to proof 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/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

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[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" (8 May 2026).

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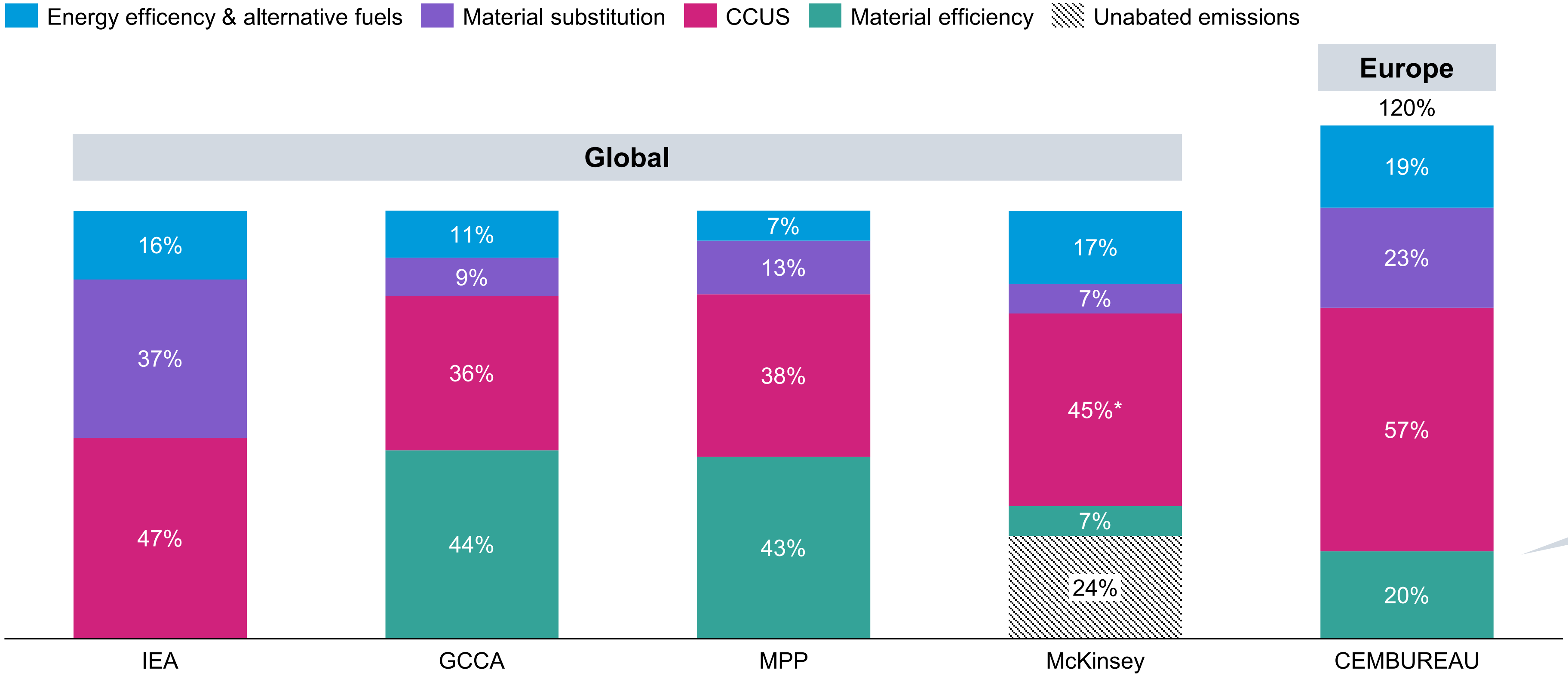
Different roadmaps consider efficiency, material substitution, and CCUS as key decarbonization levers, with CCUS abating ~36-50%

Comparison of global cement and concrete decarbonization levers by 2050

Percentage share of CO_2 emissions abated by key levers



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" (8 May 2026).

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