MAKING NET-ZERO CONCRETE AND CEMENT POSSIBLE

An industry-backed, 1.5°C-aligned transition strategy

CONCRETE AND CEMENT TRANSITION STRATEGY / 2023

MISSION
POSSIBLE
PARTNERSHIP

Founded by

Energy
Transitions
Commission

RMI
ENERGY. TRANSFORMED.

WE MEAN
BUSINESS
COALITION

WORLD
ECONOMIC
FORUM

THE MISSION POSSIBLE PARTNERSHIP

At current emissions levels, staying within the global carbon budget for 1.5°C might slip out of reach in this decade. Yet efforts to slow climate change by reducing greenhouse gas (GHG) emissions run into a central challenge: some of the biggest emitters of GHGs into the atmosphere – transportation sectors like aviation, shipping, and trucking, and heavy industries like steel, aluminium, cement/concrete, and chemicals manufacturing – are the hardest to abate. Transitioning these industries to become climate-neutral requires complex, costly, and sometimes early-stage technologies and direct collaboration across the whole value chain, including companies, suppliers, customers, banks, institutional investors, and governments.

Catalysing these changes is the goal of the Mission Possible Partnership (MPP), an alliance of climate leaders focused on supercharging efforts to decarbonise these industries. Our objective is to propel a committed community of carbon-intensive industry CEOs, together with their financiers, customers, and suppliers, to agree and, more importantly, to act on the essential decisions required for decarbonising heavy industry and transport. Founded by the Energy Transitions Commission (ETC), RMI, the We Mean Business Coalition, and the World Economic Forum (WEF), MPP will orchestrate high-ambition disruption through net-zero industry platforms for seven of the world's hardest-to-abate sectors: aviation, shipping, trucking, steel, aluminium, cement/concrete, and chemicals.

The foundation of MPP's approach: 7 Sector Transition Strategies

Transitioning heavy industry and transport to net-zero GHG emissions by 2050 – while complying with a target of limiting global warming to 1.5°C from preindustrial levels – will require significant changes in how those sectors operate. MPP facilitates this process by developing Sector Transition Strategies for all seven hard-to-abate sectors.

A Sector Transition Strategy* *is a suite of user-friendly tools (including a report and an online explorer) aiming to inform decision makers from the public and private sectors about the nature, timing, cost, and scale of actions necessary to deliver net zero within the sector by 2050 and to comply with a 1.5°C target.

The objectives of the MPP Sector Transition Strategies are:

1. **To demonstrate industry-backed, 1.5°C-compliant pathways to net zero:** The focus is on in-sector decarbonisation and galvanising industry buy-in across the value chain.

2. **To be action-oriented with clear 2030 milestones:** MPP quantifies critical milestones for each sector in terms of its required final energy demand, upstream feedstock resources, and capital investments. Through these milestones, MPP wants to lay the foundation for tangible, quantitative action through collaboration among industry, policymakers, investors, and customers.

3. **To be transparent and open:** MPP's long-term goal is to fully lay open the internal machinery of the Sector Transition Strategies, that is, to make its Python models open source and all data inputs open access. In addition, MPP is developing online explorers that bring the Sector Transition Strategy reports to life: individual users will be able to explore the results of the reports and customise model input assumptions, study the impact of individual levers, and dive deeper into regional insights.

4. **To break free from siloed thinking:** The transition of a sector to net zero cannot be planned in isolation since it involves interactions with the broader energy system, for instance, via competing demands for resources from multiple sectors. All MPP Sector Transition Strategies are based on similar assumptions about the availability and costs of technologies and resources like electricity, hydrogen, or sustainable biomass. By providing a harmonised, cross-sectoral perspective, we intend to inform decision makers with a fair, comparable assessment of transition strategies for all seven sectors.

Based on its Sector Transition Strategies, MPP intends to develop practical resources and toolkits to help operationalise industry commitments in line with a 1.5°C target. Among others, the quantitative results of the Sector Transition Strategies will inform the creation of standards, investment principles, policy recommendations, industry collaboration blueprints, and the monitoring of commitments. These will be developed to expedite innovation, investments, and policies to support the transition.

Goals of the MPP Concrete and Cement Sector Transition Strategy

In this report, we explore the potential to reduce emissions associated with the production of concrete and cement. This analysis builds on the Global Cement and Concrete Association's (GCCA's) *Concrete Future: The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete* and the European Cement Research Academy's (ECRA's) 'Technology Papers 2022.'[1] The analysis was developed with input from GCCA membership and the wider concrete and cement community as part of the Concrete Action for Climate initiative (initiated by WEF and the GCCA in 2021).

The Concrete and Cement Transition Strategy is the first roadmap developed with industry and anchored in a granular economic model for how the global concrete and cement sector can reach net-zero GHG emissions by 2050 while also complying with a 1.5°C target, as part of a coherent set of roadmaps for all heavy industry sectors. In addition, it moves from strategic thinking to near-term milestones, providing recommended actions industry, concrete and cement buyers, policymakers, and financial institutions can take to unlock the transition in this decade. The strategy focuses in particular on how to unlock new technology and innovation to address the sector's challenges.

The scenarios presented in this report are not forecasts but instead illustrate potential trajectories for the concrete and cement industry under different assumptions made at the time of writing this report (2022–23). These assumptions may be updated as policy, finance, and industry stakeholders move to develop, commercialise, and scale the required technologies and policy regimes for this transition.

Stakeholder support for MPP's Concrete and Cement Transition Strategy

This effort benefitted from the input of a number of organisations who were consulted on the model inputs and architecture and acknowledge the general thrust of the arguments made in this report, but should not be assumed to agree with every finding, calculation or recommendation. These organisations/companies agree on the importance of the ambition to limit global warming to 1.5°C and reach net-zero GHG emissions in heavy industry and transport by mid-century, and share a broad vision of how to achieve the transition.

This report will help decision makers around the world feel more confident that it is possible to meet global concrete and cement demand and simultaneously reduce emissions from the sector to net zero by 2050. It should also inspire belief that the critical actions required in the 2020s to set the sector on the right path are more clear than before, and that the industry would like to collaborate with its value chain and policy makers to achieve those goals. Indeed the transition is predicated on enabling policy and green financial frameworks to support and expedite the transition.

gcca Global Cement and Concrete Association

acemy
ARGOS
architecture 2030
bp
CarbonOrO
CLF Carbon Leadership Forum
CEMEX
Dalmia Bharat Limited
FLSmidth
fortera
FCA Future Cleantech Architects
Heidelberg Materials
HOLCIM
KHD HUMBOLDT WEDAG
MISR CEMENT GROUP مجموعة مصر للأسمنت
NORM əSL SEMENT
Pacasmayo
SECIL Shaping ideas
TCC THE FUTURE IS WORTH IT

ACKNOWLEDGEMENTS

This report was prepared by the Mission Possible Partnership.

With contributions from Faustine Delasalle (MPP), Laetitia de Villepin (ETC), Thomas Guillot (GCCA), Radhika Lalit (RMI), Yvonne Leung (WEF), Andrew Minson (GCCA), Eveline Speelman (ETC).

The development of the analytics and report was led by: Marten Ford (ETC), Wouter Vink (ETC).

And supported by: Zhinan Chen (RMI), Timon Rückel (ETC), Ben Skinner (RMI), Floor van Daam (ETC), Emile Wesseling (ETC).

We thank the European Cement and Research Academy, led by Martin Schneider, with Johannes Ruppert, Dennis Behrouzi, Jens Romeike, and Kristina Fleiger, for their support developing the analytics and for this report.

We also thank all workshop participants, reviewers, and other collaborators for offering guidance, assessing the analytical work, and providing helpful comments and feedback in their review throughout the project.

The report was edited and designed by M. Harris & Co.

PREPARED BY

Mission Possible Partnership (MPP)

Founded by the ETC, RMI, the We Mean Business Coalition, and the World Economic Forum, the Mission Possible Partnership (MPP) is an alliance of climate leaders focused on supercharging the decarbonisation of seven global industries representing 30% of emissions: aviation, shipping, trucking, steel, aluminium, cement/concrete, and chemicals. Without immediate action, these sectors alone are projected to exceed the world's remaining 1.5°C carbon budget by 2030 in a Business-as-Usual scenario. MPP brings together the world's most influential leaders across finance, policy, industry, and business. MPP is focused on activating the entire ecosystem of stakeholders across the entire value chain required to move global industries to net-zero. **www.missionpossiblepartnership.org**

Energy Transitions Commission (ETC)

ETC is a global coalition of leaders from across the energy landscape committed to achieving net-zero emissions by mid-century, in line with the Paris climate objective of limiting global warming to well below 2°C and ideally to 1.5°C. Our commissioners come from a range of organizations – energy producers, energy-intensive industries, technology providers, finance players, and environmental NGOs – which operate across developed and developing countries and play different roles in the energy transition. This diversity of viewpoints informs our work: our analyses are developed with a systems perspective through extensive exchanges with experts and practitioners. **www.energy-transitions.org**

RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing. **rmi.org**

World Economic Forum

The World Economic Forum is the international organization for public–private cooperation. The Forum engages the foremost political, business, cultural, and other leaders of society to shape global, regional, and industry agendas. Learn more at **www.weforum.org**.

CONTENTS

EXECUTIVE SUMMARY

ELEVEN CRITICAL INSIGHTS ON THE PATH TO A NET-ZERO CONCRETE AND CEMENT SECTOR

1. Concrete and cement are essential to economic development. However, they contribute 7%–8% of global CO_2 emissions and the sector is one of the hardest to abate.

With a global demand of 14 billion cubic meters (m^3) in 2020,[2] concrete is the world's most widely used material after water. It is an essential part of everyone's lives, critical to buildings, transportation, and other infrastructure, and produced in every country, which makes concrete and cement markets highly local. The concrete and cement industry emits roughly 2.6 gigatonnes (Gt) of CO_2 per year, accounting for 7%–8% of total global CO_2 emissions. As shown in Exhibit A, 88% of the emissions in the concrete production process comes from the clinker-making phase.

Immediate action is necessary: The year 2050 is just one investment cycle away owing to the industry's long-lasting capital assets. Over the next 10 years, major new investments should be net-zero-compatible and decarbonisation technologies should be deployed on a large enough scale to trigger cost reductions and enable significant greenhouse gas (GHG) emissions reductions in the following years.

Decarbonising the sector faces four key challenges, making it one of the hardest-to-abate sectors:

1. **Process emissions from clinker production:** Today, clinker is made from a mix of two raw material components, limestone and clay, which generate CO_2 emissions as they are heated during the calcination process. This accounts for 53% of the sector's emissions.

2. **High kiln temperature:** Thirty-five percent of the sector's CO_2 emissions comes from burning fuels to reach the 1,450°C required for the mineralogical transformation of the limestone with the other raw materials inside the rotary kiln. Commercially available kilns currently use fossil fuels.

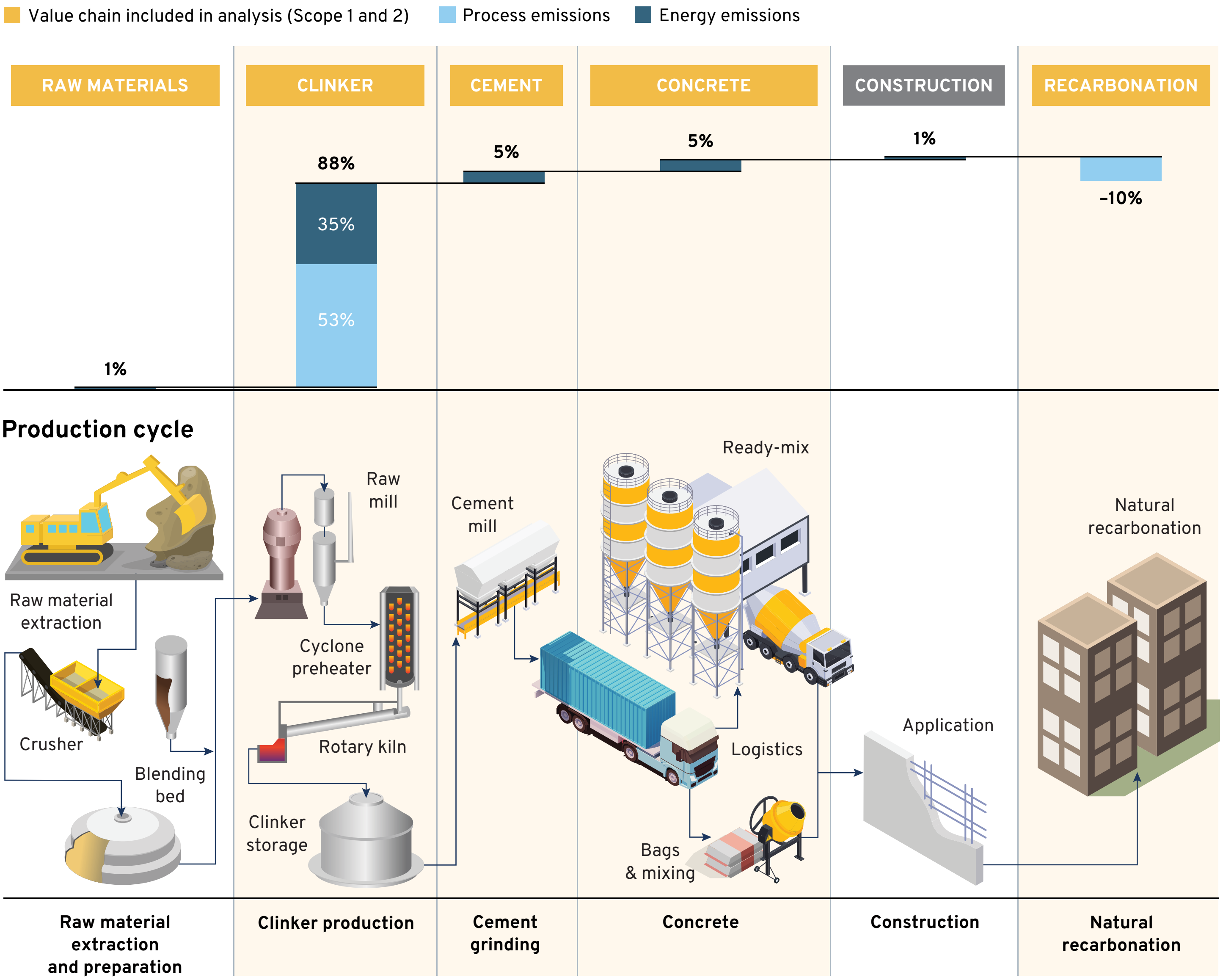
3. **Significant projected demand growth:** Global cement production capacity increased by 30% in the last decade.[3] With no further action, demand for cement is expected to grow by 14% from 2020 to 2030, and another 22% by 2050, driven by population growth and economic development in Global South countries outside of China.[4]

4. **Highly localised market:** Concrete and cement have historically been inexpensive and common and therefore have been a localised market. Because they are usually produced close to their use (less than 50 km for concrete and 250 km for cement), the decarbonisation of concrete and cement depends on local resources and infrastructure, with limited significant relocation of industrial sites. Region-specific decarbonisation pathways are therefore critical.

EXHIBIT A

The majority of emissions in the concrete production cycle come from clinker production

Percentage of total CO_2 emissions of the concrete and cement sector



Note: This illustration covers Scope 1 and 2 emissions and includes total raw material extraction. Other construction materials are not considered in this analysis.

Source: McKinsey & Company, *Laying the Foundation for Zero-Carbon Cement* (2020); and Global Cement and Concrete Association, *GCCA Concrete Future – Roadmap to Net Zero* (2021)

2. The concrete and cement sector can reach net zero by 2050 and stay within its sectoral 1.5°C carbon budget if concrete is used more efficiently, the clinker content of concrete is decreased, and remaining production emissions are brought close to zero.

If no action is taken, cumulative emissions could reach 98 Gt CO_2 between 2022 and 2050, an overshoot of more than 100% against a 1.5°C carbon budget of 47 Gt CO_2 for the sector.[i] Staying below this threshold requires the rapid and concomitant deployment of the following existing and new decarbonisation levers (Exhibits B and C detail a net-zero deployment pathway, emissions reductions levers, and key characteristics):

A. **Using concrete more efficiently** by implementing structural system and design improvements, extending building life spans, using alternative building materials, and reusing concrete elements to reduce the demand for concrete

B. **Reducing process emissions,** by:

  - **Using less clinker per unit of cement** by using less emissions-intensive supplementary cementitious materials (SCMs)
  - **Using less cement per unit of concrete** by increasing the effective strength of cement and industrialising the concrete production process
  - **Bringing alternative low or zero carbon chemistries to market** (e.g., alternative binders, decarbonated raw materials)

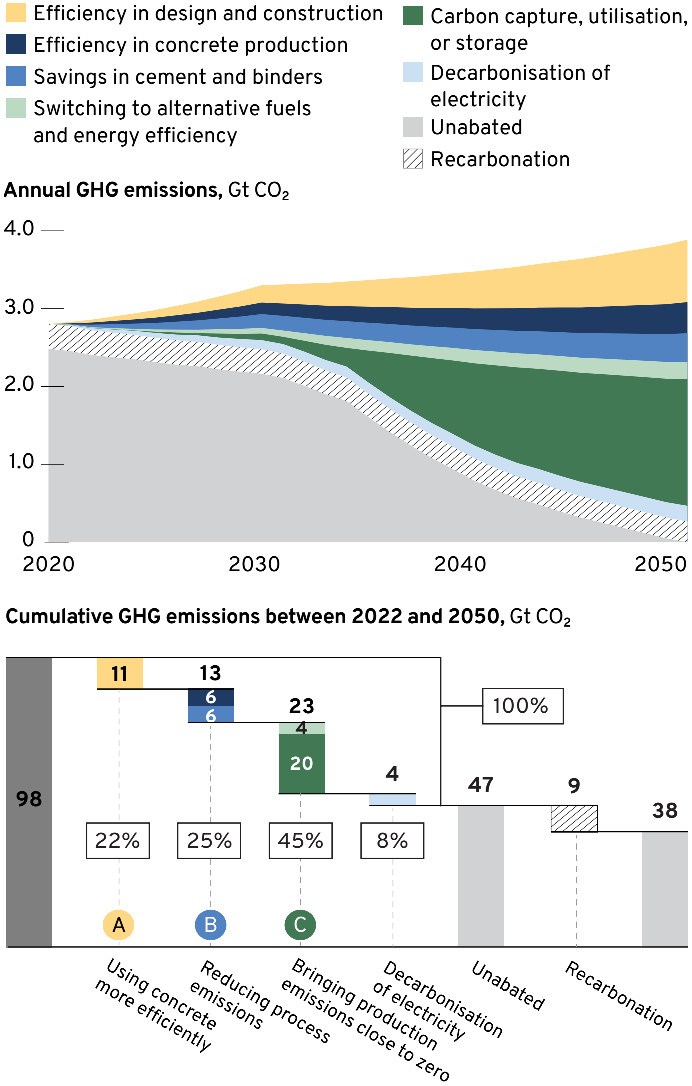
C. **Bringing production emissions close to zero,** by:

  - **Reducing and eventually eliminating heat emissions** by deploying thermal efficiency measures and replacing fossil fuels with waste and biofuels, hydrogen, or electrification
  - **Capturing remaining process and heat emissions,** in order to store or utilise them (carbon capture and utilisation or storage [CCU/S])

In addition to these decarbonisation levers, concrete reabsorbs carbon dioxide throughout its life cycle through a phenomenon called **recarbonation,** which is a carbon sink and is estimated to absorb 9 Gt CO_2 by 2050.

EXHIBIT B

Net zero, 1.5°C-aligned concrete and cement sector



Note: Annual GHG emissions include includes Scope 1 and 2 emissions. Scope 3 upstream emissions would add approximately 3.8 Gt CO_2e of cumulative emissions from 2022 to 2050. Decarbonisation of electricity involves electricity demand for kilns, grinders, and carbon capture.

Source: MPP analysis (2022)

---

[i] The sectoral 1.5°C carbon budget is calculated as of the beginning of 2022 at a 50% probability of achieving a 1.5°C target. It has been broken down from a global carbon budget provided by the Intergovernmental Panel on Climate Change (IPCC) to individual sectors following an average of the sectoral allocations of the International Energy Agency's Net Zero by 2050 analysis and the One Earth Climate Model.

EXHIBIT C

Key technologies and levers for decarbonising the concrete and cement sector

		METHOD OF REDUCING EMISSIONS	EMISSIONS-REDUCTION POTENTIAL	TECHNOLOGY READINESS LEVEL	COST IMPLICATIONS *(\$/t CO_2 avoided in 2040)*	KEY BARRIERS FOR LARGE/FAST DEPLOYMENT
Using concrete more efficiently		Reduces demand for concrete	100% carbon reduction on decreased demand.	• Most methods: 9	Negative or negligible operating costs and investments.	• Consumer demand based on lack of awareness or buyer technical resources • Coordination across multiple actors in value chain
Reducing process emissions	Use of supplementary cementitious materials (SCMs)	Reduces demand for clinker	Compared with ordinary portland cement: • Fly ash: 4%-35% • Limestone: 2%–16% • GGBS: 31%–73% • Calcined clay mixed with limestone: 40%	• Existing SCMs (limestone, fly ash, GGBS): 9 • Calcined clay: 9 • Slag from new steel production methods: 3–4	-\$11 to -\$20/t CO_2	• Consumer demand based on lack of awareness or buyer technical resources • Standards • Local availability and production facilities
	Alternative chemistries *(decarbonated raw materials and alternative binders)*	Reduces/ eliminates emissions associated with clinker production	Significant; depending on the raw materials of the alternative chemistries. Could increase if process has lower heat demand than traditional clinker making.	• Non-carbonate sources: 3 • Magnesium silicates: 3 • Raw clay: 6 • Carbonation of calcium silicates: 8	Uncertain – early estimates suggest potentially lower cost than CCU/S	• Early stage of technology development • Standards and consumer preference • Sourcing raw materials at scale
Bringing remaining emissions close to zero	Fuel switching (to waste)	Reduces emissions associated with heat for clinker production. Requires biogenic waste or CCU/S for net zero	Up to 35% if waste is biogenic or industrial waste with CCU/S (covers only heat emissions)	• Industrial and biomass wastes: 9	-\$20 to -\$30/t CO_2	• Permitting and regulation • Sourcing waste biomass • Combining waste with CCU/S
	Electricity/ hydrogen	Reduces on-site emissions associated with heat for clinker production	Up to 35% if electricity and hydrogen are zero carbon (covers only heat emissions)	• Hydrogen: 4 • Electricity: 4–5	Breaks even with carbon capture if electricity price is less than \$32/MWh or H_2 price is less than \$2.5/t H_2	• Early stage of tech. development and lack of widespread availability • High costs of hydrogen and electricity compared with coal
	Carbon capture, utilisation, or storage (CCU/S)	Captures carbon associated with clinker process and heat for clinker production, associated with storage or long-term usage	Up to 95% (depends on capture rate)	• Post-combustion: 8–9 • Oxyfuel: 6 • Indirect calcination: 7	Highly dependent on location: \$160–\$190/t CO_2	• Developing transport and storage and usage • Regulatory framework • High costs

Note: Carbon savings are relative to concrete production emissions outlined in Exhibit A.

Source: MPP analysis; IEA, **https://www.iea.org/reports/energy-technology-perspectives-2020**; Mineral Products Association; LC3

3. Efficiency in design and construction can reduce concrete demand and thereby reduce cumulative emissions by 11 Gt (22%) by 2050 without compromising safety and durability. This requires significant changes in construction operating models and standards, supported by the whole value chain.

Global demand for concrete construction – buildings and infrastructure – will keep increasing to provide housing, sanitation, clean energy, and other development needs. Concrete's properties make it a versatile material to deliver long-lived projects that are resilient to fire, wind, water, and high-temperature events.

However, construction can be delivered in a more effective manner. Building owners and designers and buyers of concrete can pull **many levers to deliver demand reductions**, including topology optimisation, structural solutions, lean design, reuse of concrete elements, and extension of building life spans (Exhibit D). Altogether, these levers could reduce demand for concrete by 22% by 2050.

In addition, **alternative construction materials** for buildings, such as timber, clay, straw bale, or bamboo, can be used in some cases instead of or in combination with concrete, although these have different performance levels. The availability of sustainably produced timber will likely constrain growth of its use in the coming decades,[5] and the use of timber is estimated to stay below a 5% market share penetration in construction materials.[6]

Enabling more efficient use of concrete will require **increasing awareness of and tightening regulations around carbon emissions associated with building construction and construction sites (or embodied emissions),** and focusing and measuring of the potential **financial benefit of cutting material inputs** and hence reducing the total cost associated with concrete in construction projects. These changes should be achieved while maintaining the strength, durability, and other performance properties that the structures require.

It is essential to stimulate material efficiency levers to their maximum potential in the upcoming decade given their low costs and high emissions-reduction potential. This will require significant changes in policy, operating models, and standards setting, as well as collaboration across the value chain.

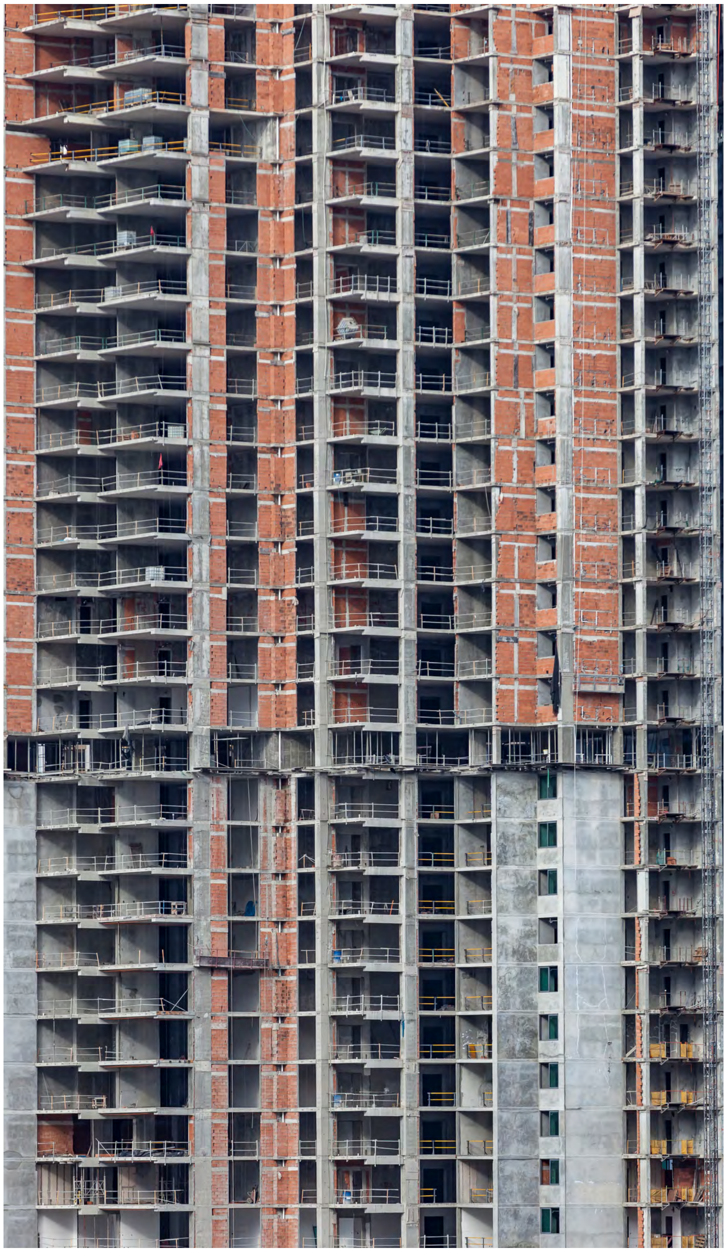


EXHIBIT D

Using concrete more efficiently reduces emissions by 22% by 2050

↑ High cost ↓ Low cost ● High amount of barriers ○ Low amount of barriers

LEVER		DESCRIPTION	REDUCTION	COST	BARRIERS
Topology optimisation		Optimise positioning and arrangement of components to reduce material requirements	1%–3%	↑	◑
Structural solutions	Precasting	Precasting in reusable mold eliminates on-site waste, improves specification accuracy	2%–4%	↑↑	◕
	Post-tensioned structures	Reduce needed concrete volume by increasing strength through tensioning steel within concrete to counteract external loads of bending elements (beams/slabs)	2%–4%	↑↓	○
	Voids, coffers, fill	Omit or replace concrete volumes that contribute little to structural space with fill or voids	2%–6%	↑	◑
Lean design		Use automated design methods to explore options that use less material	5%–9%	↓	◔
Reuse of concrete elements		Reuse concrete component parts from dissembled structures, reducing need for new concrete elements	0%–1%	↑	●
Extension of building life span		Prevent building new concrete-based structures by limiting unnecessary demolition of current stock of structurally sound assets	1%–5%	↓	◕
Alternative materials in construction		Use alternative materials in construction	Up to 5%	↑	◕

Note: Cost is the approximate cost of realising the savings, excluding the benefits from reduced concrete use.

Source: **UN Environment et al**, **Material Economics**, **LC3**, **Holcim**, **Institute of Civil Engineering**, **IEA**, **IEA Energy Technology Perspectives 2020**, **Chatham House**, **RMI**, Expert Value chain interviews

4. Process emissions can be reduced in the short term by using less clinker in cement and less cement in concrete, resulting in a cumulative emissions savings of 25% by 2050. Alternative chemistries could offer a solution to process emissions when they reach commercialisation.

Reducing process emissions can be achieved by pursuing three key levers: (1) use less clinker in cement, (2) use less cement in concrete, or (3) deploy alternative breakthrough solutions as they become available:

1. **Clinker content can be reduced** by partially replacing clinker with SCMs, which reduces carbon emissions while maintaining cement performance. This lever can be implemented today, with scalable options like calcined clay and natural pozzolans available for deployment. The global average clinker-binder ratio is currently 0.63,[ii] with regional values ranging from 0.53 to 0.96 owing to local preferences and raw material availability. Reducing the global average clinker-binder ratio to 0.52 could increase the volume of SCMs used by 26% in 2050 and deliver a 5%–15% reduction in costs and 18% of cumulative emissions savings (Exhibit E).[iii] Emissions could potentially be reduced even further in specific applications: today, slag achieves a ratio of 0.2, but only in specific use cases, and it is challenging to expand given availability issues.

   Using SCMs also reduces the volume of landfilled materials and enhances circularity, as many SCMs are industrial by-products. However, because SCMs are bulk materials, local and regional sourcing is important. Key SCMs that will accelerate the transition to net zero include existing mature solutions as well as emerging ones:

   - **Fly ash** and **ground granulated blast-furnace slag** (GGBS) dominate the SCM market today. Their supply is expected to fall as coal and blast furnaces are phased out,[iv] but large stockpiles will allow them to continue playing a significant role in the short and medium term. Additionally, innovative fly ash such as that produced from calcium silicate cement and slag from new hydrogen-based production methods, although still in early development, could play a significant role.

   - **Ground limestone** is used today in the United States and Europe and has potential to expand given the availability of limestone.

   - **Natural pozzolans** can be used as an additional SCM in areas where they are abundant (e.g., volcanic regions), but their availability varies significantly by region.

   - **Calcined clay** is also a proven SCM, expected to increase significantly given its global availability.

   - **Recycled concrete fines from construction demolition wastes** are being explored as an emerging SCM, but new policies and regulations are required to make the business case profitable, as well as improvements in building design and waste management.

   - **Biomass ashes and silica fumes** have already been developed but only deployed in specific use cases.

The deployment of SCMs is regulated by cement and concrete standards, as well as client and project designer specification and contractor procurement. Requests for low or no SCM content are often technically unwarranted and based on reuse of previous projects' specifications or lack of awareness.

Policymakers should accelerate:

- The update of existing standards to allow for larger SCM adoption and deployment of new cement chemistries, when their technical performances have been demonstrated

- The development of performance-based concrete and cement standards, as they allow suppliers to bring new SCMs solutions to market and at higher percentage contents. Standards also provide clear guidance for users, with clear certification of performance, safety, and use cases.

In addition, green public procurement can be structured to ensure government-procured projects have lower embodied carbon content, including a greater use of SCMs.

[ii] Clinker-binder ratio demonstrates the amount of clinker used in concrete. Binder means all material in concrete such as cement, fly ash, ground granulated blast-furnace slag, and limestone fines.

[iii] Regional variations range from 0.47 to 0.55 in MPP's Net-Zero scenario and from 0.42 to 0.49 in the Rapid Barrier Elimination scenario.

[iv] New GGBS supply is expected to fall 80%–100% as the steel industry switches to alternative technologies (MPP Steel Sector Transition Strategy).

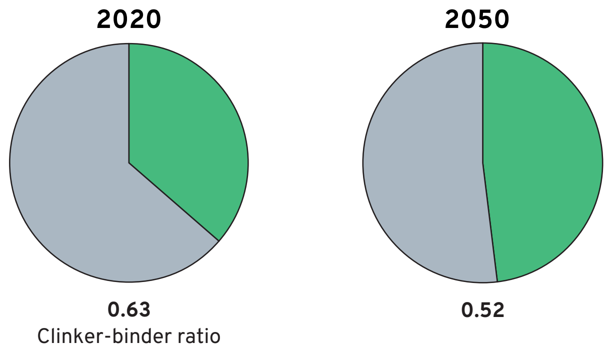
EXHIBIT E

New SCMs can play a significant role in 2050 and reduce emissions by 18% in 2050 and costs by 5%–15%

SCMs can reduce emissions per tonne by 18% and costs by up to 15% in 2050 …

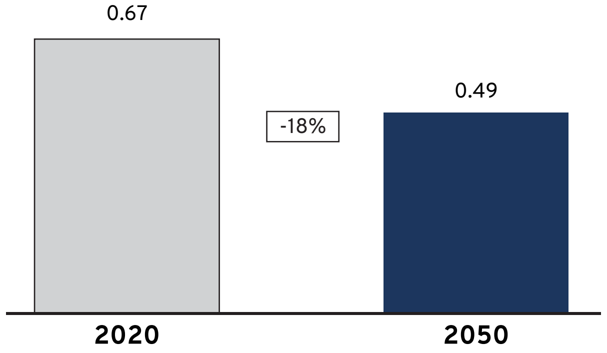
CEMENT COMPOSITION

Average cement mix ▨ Clinker 🟩 SCMs



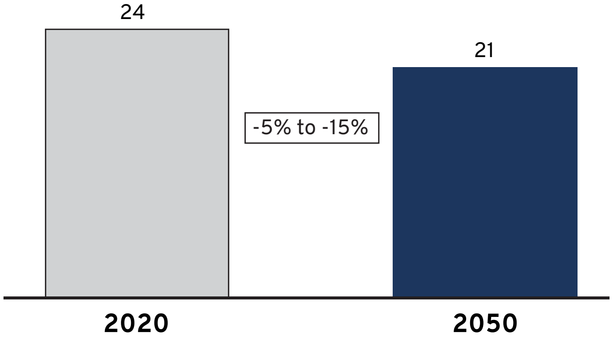
EMISSIONS

t CO_2/t cement, based on low-carbon SCMs



COSTS

$/t cement, cost reductions depend on SCMs used

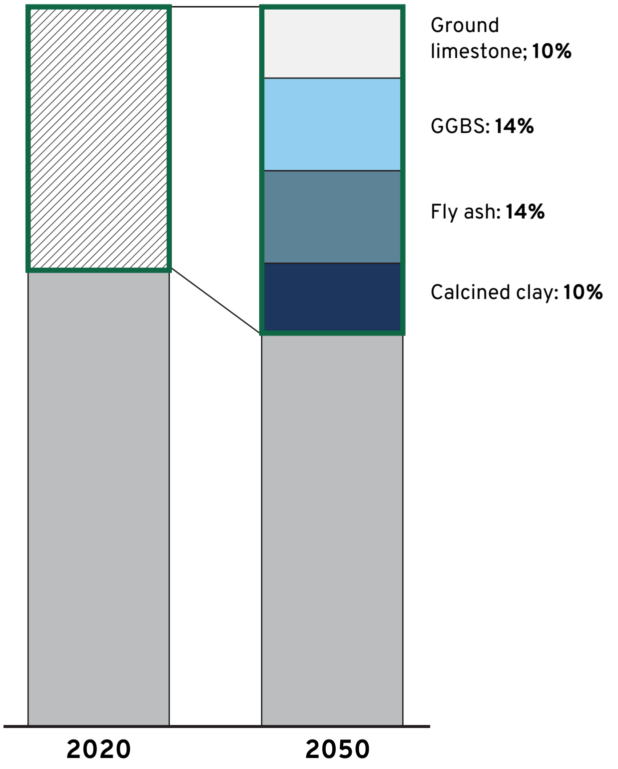


Note: SCM availability is on a global level compared with limestone.

… and they are expected to increase by 26% in volume by 2050

GLOBAL CEMENT MIX

% of mass



AVAILABILITY OF SCMs

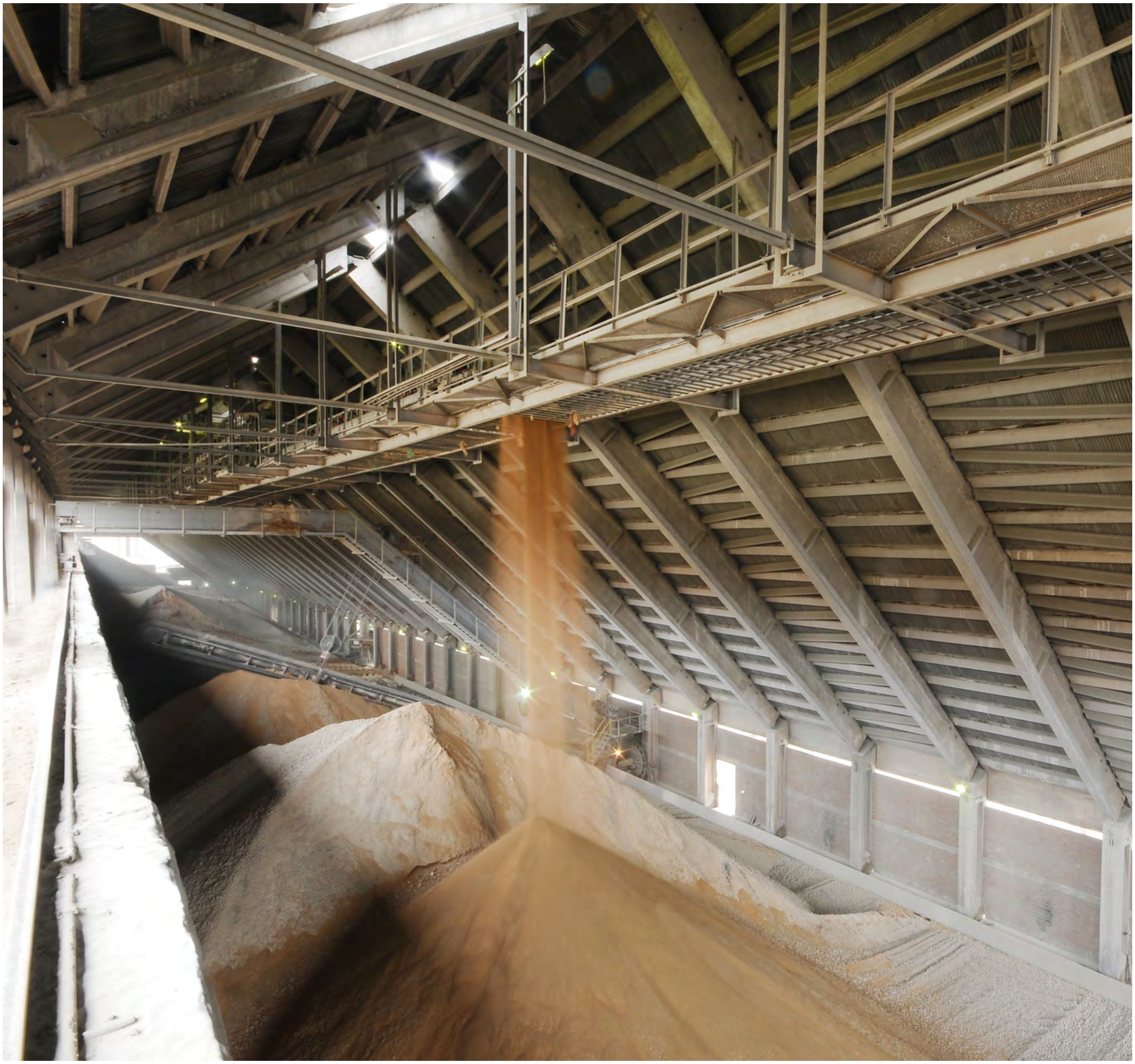
	Present	2050
Ground limestone	High	High
GGBS	High	Low–Medium (higher in developing economies)
Fly ash	High	Low–Medium (higher in developing economies)
Calcined clay*	High	High
Others	-	-

*While Calcined clay raw materials are widely available, the SCM needs to be complemented with real-world production capacity

Source: GCCA Clinker Substitutes; ECRA Technology Papers 2022; interviews with experts

2. In addition, it is possible to **use less cement in concrete** by improving mix design, grading aggregates better, using admixtures more effectively, and improving quality control, resulting in a lower use of clinker. This could deliver cumulative emissions savings of up to 9%. The industrialisation of concrete production facilitates this higher material efficiency through the shift from bagged cement mixed on-site to increased off-site concrete mixing at ready-mix plants and deployment of precast factories.

3. In the medium to longer term, process emissions (currently at low technology readiness levels [TRLs]) could be brought to zero if **alternative chemistries break through**. If alternative chemistries account for 5% of supply by 2050, they would reduce cumulative by 3%, according to the Mission Possible Partnership's (MPP's) scenarios. Some promising examples of alternative chemistries include carbonation of calcium silicates, reactivation of $CaCO_3$, and bio-based cement. Alternative chemistries could play a valuable role in reducing clinker use or reducing the carbon intensity of clinker production, thereby serving as alternatives to carbon capture from cement production.



5. Abating heat-related emissions is possible by replacing fossil fuels with waste (biogenic or coupled with CCU/S), complemented with hydrogen and/or electrification as soon as these technologies reach market readiness.

Energy use in kilns represents 35% of sector emissions. The predominant fuels currently used are coal and petcoke (82%). Other fuels include natural gas (9%), industrial wastes (6%), and biogenic waste (3%). This energy can be decarbonised by instead using low- or zero-emissions fuels, including nonreusable nonrecyclable waste streams (available now) and hydrogen and electrification (which both require innovation and cheap, abundant zero-carbon electricity to reach cost-competitiveness):

A. **Using waste from biological or industrial origins** reduces emissions and costs and increases circularity by preventing waste from going to landfills or being incinerated. The mineral content from waste can also reduce the raw materials needed in clinker production through co-processing. The technology is ready and widely used in Europe. The share of waste as fuels (i.e., waste of fossil origin and biogenic waste) in cement kilns is forecast to increase from around 6% today to around 40% by 2050, provided favourable regulation is developed globally. However, the mix of waste is vital in determining its role in the transition. If waste is not fully biogenic, carbon capture is still required to lower emissions to a net-zero pathway, offering the possibility of negative emissions on the biogenic share. Emissions of non-CO_2 air pollutants must also be subject to emissions control measures and monitoring to enable the safe treatment of waste. Burning waste presents the benefit of reducing emissions today with a technology-ready solution, as well as participating in the decarbonisation of the waste sector. It can be complemented by other net-zero solutions such as low-carbon electricity and hydrogen as they become available.

B. **Low- or zero-carbon hydrogen** could be mixed with other fuels such as waste (as demonstrated in a study from the Mineral Product Association[7]) and could be cost-competitive if and where hydrogen costs are less than $2.5/kg. Hydrogen use in cement production is currently in the early stages of development (TRL 4) and further trials are required to understand how hydrogen could be most effectively deployed in the sector.

C. **Kilns might be partially or fully electrified, using zero-carbon electricity.** This solution is at an early stage of development (TRL 4). It will only be competitive and scalable in locations with abundant low-cost low-carbon power, as the energy requirements are significant. Assuming that 10% of total energy demand is met by electricity, 550 terawatt-hours of low-carbon electricity would be required annually (0.5% of projected total global electricity supply in 2050). To compete with the average cost of CCU/S in 2050, electrified kilns would need access to electricity for less than $32 per megawatt-hour (though this will vary depending on local costs).

How a plant owner chooses to decarbonise heat emissions will depend on local availability and pricing of zero-carbon energy sources. As these technologies only decarbonise energy emissions, they will need to be used in addition to decarbonisation options tackling process emissions, thus adding to the total decarbonisation cost. In the short term, technology-ready solutions (e.g., use of waste) are the most cost-effective choice, but as net zero becomes the objective, these should be complemented with full decarbonisation options like carbon capture for process and heat emissions or bundled with other technologies such as low-carbon hydrogen. The use of hydrogen or electric kilns has the promise of a purer CO_2 stream of process emissions, resulting in cheaper carbon capture.

6. Carbon capture coupled with utilisation or storage is necessary to address remaining process and energy-related emissions. CCU/S could be required at a scale of 1.2 to 1.6 Gt of CO_2 per year by 2050, representing 11%–23% of forecast captured carbon across all sectors in 2050.

CCU/S is one of the most developed technological options for addressing process and heat emissions in cement kilns, and commercial-scale plants are already starting to be deployed today.

The decision on what to do with the captured CO_2 depends on local conditions. In industrial clusters where transport and storage projects have multiple users (such as chemicals and removal options), cement plants can make use of shared CO_2 storage and transport infrastructure, achieving economies of scale. For cement plants in geographically isolated areas or far from geological storage sites, carbon capture can be combined with on-site or close usage/storage options, such as use in aggregates or enhanced CO_2 mineralisation. When CO_2 is captured and used for another purpose such as e-fuels production, very careful consideration will have to be given to the carbon footprint. In the long term, in order for the sector to be on a 1.5°C pathway, carbon use has to offer a form of permanent storage, for example through aggregates or long-lived plastics, depending on their recycling potential.[v]

Deploying CCU/S on an industrial scale still faces challenges:

A. **Cost challenges:** Without policy support, applying carbon capture to cement plants can double cement-making costs compared with today, including carbon transport and storage costs, though with significant regional variations. The cost challenges associated with CCU/S are more prominent in emerging markets. The cost-competitiveness of carbon capture is highly dependent on a carbon price that, if at or above the capture cost, would naturally help bridge the cost premium.

B. **Infrastructure and investment challenges:** In order to deliver 1.2 to 1.6 Gt of CO_2 capture by 2050, 90% of existing cement production sites need to be equipped with capture technologies in 2050. The captured carbon from the cement sector would then represent 11%–23% of all global forecast CCU/S deployment across sectors.[8] Because cement and concrete use is geographically dispersed, almost all countries will require CCU/S infrastructure as well as policies to incentivise and manage this growing infrastructure, including regions where storage potential is challenging.

C. **Technology risks:** While the TRLs of the different capture technologies range from 4 to 9,[vi] capture rates and energy needs pose significant challenges:

- To be 1.5°C aligned, carbon capture processes in cement have to deliver at least 95% capture rates, increasing from today's rate of 90%. Residual Scope 1 emissions (of the order of 80–100 megatonnes [Mt] CO_2 in 2050) are covered by the savings offered from recarbonation (approximately 240 Mt CO_2 per year in 2050). However, if the capture rate fails to reach sufficient levels, or if the deployment of CCU/S fails to cover 90% of the production sites, further savings from other levers or carbon dioxide removal technologies would be required.
- Without new capture technologies (such as oxyfuel), post-combustion carbon capture represents a significant energy demand (1.5 to 7 megajoules/kg CO_2,[9,vii] an energy use increase of up to 60%, which could be delivered through local waste heat or off-site low-carbon heat production and low-carbon electricity provision).

---

[v] A full description of the challenges and considerations of usage can be found in Energy Transitions Commission, Carbon Capture, *Utilisation and Storage in the Energy Transition: Vital but Limited*, 2022.

[vi] See details in full report (Box 7).

[vii] Specific primary energy consumption unit of CO_2 avoided.

These challenges and risks can be more pronounced in emerging and developing economies, as limited financial resources, lack of access to low cost of capital, regulatory barriers, high cost of electricity, and limited access to new technologies as well as lack of technical knowledge and skills can collectively hinder the deployment of CCU/S technology and infrastructure at scale. Addressing these challenges requires a combination of technological advancements, financial support, capacity building, and international cooperation.

New technologies show promising potential to tackle the challenge associated with CCU/S scale-up:

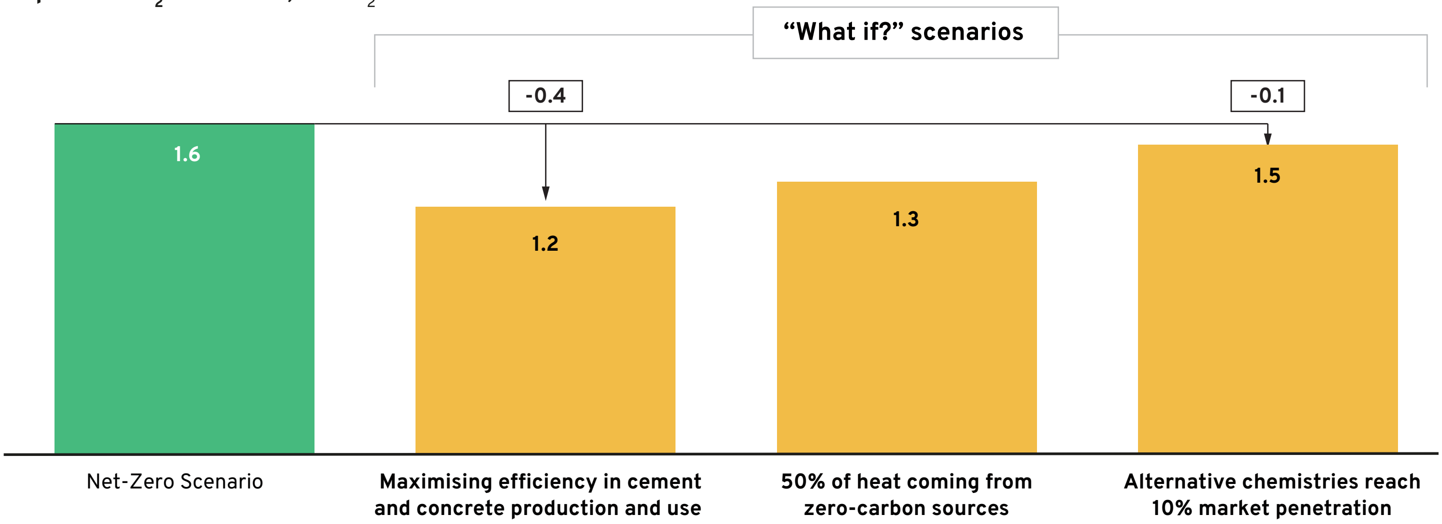
- If **new capture technologies** attain commercial deployment, they could reduce carbon capture costs through increased energy efficiency, reduced capital expenditures, and improved CO_2 capture efficiency and purity. Some of these technologies are in development (e.g., calcium looping, with a TRL of 6 to 7) and are expected to be deployed in the late 2020s.
- **Geographical challenges can be mitigated by the deployment of industrial-scale carbon dioxide mineralisation or usage in aggregates or other products** (TRL 4 to 8) for sites that are neither in an industrial cluster nor near a CO_2 transport and storage project. Other options like carbonation of industrial wastes may also emerge.

The amount of carbon capture required depends heavily on the delivery of other technologies and levers. **If efficiency levers are maximised or if low-carbon heat sources or alternative chemistries gain significant market share, the annual volume of captured carbon from cement kilns could be reduced by 0.1 to 0.4 Gt CO_2 (6% to 25% compared with the Net-Zero scenario), and more if the levers are combined.** This would significantly reduce the size and cost of the CCU/S infrastructure buildup (Exhibit F). However, in all scenarios and sensitivities modelled, carbon capture plays a significant role in decarbonising the sector.

EXHIBIT F

Further deployment of technologies or maximizing efficiency levers could reduce the captured emissions by 0.1 to 0.4 Gt CO_2

Captured CO_2 emissions, Gt CO_2



Note: These scenarios demonstrate the scale of the interaction between new technologies and CCU/S use. At this early stage, it is difficult to estimate the market penetration rates of these new technologies. Key assumptions: Maximising efficiency in cement and concrete production and use sensitivity scenario involves a reduced clinker demand by 27% by 2050. Fifty percent of heat coming from zero-carbon sources assumes that by 2050 electricity and hydrogen make up 50% of kiln heat demand. Alternative chemistry scenarios involve a 10% market penetration by 2050.

Source: MPP analysis (2022)

7. As the sector decarbonises, local conditions including access to SCMs, low-carbon energy, and carbon transport and storage infrastructure will determine the appropriate set of solutions.

Cement is a highly localised market: plants are traditionally sited based on the location of suitable raw materials supply, including limestone, and proximity to end markets. As the industry transitions to net zero, access to low-carbon solutions will play an increasingly important role in the strategic choices of concrete and cement firms, including retrofitting or retiring existing plants, or locating new plant (Exhibit G). Key location-specific criteria for a low-carbon plant include:

A. **Access to raw materials:** The availability of SCMs and thus the cost to replace clinker with SCMs varies significantly locally due to differences in natural resources and industrial landscape, as many SCMs are industrial by-products. Local quarry access can also improve the business case for alternative chemistries, for example, those using calcium silicate rocks.

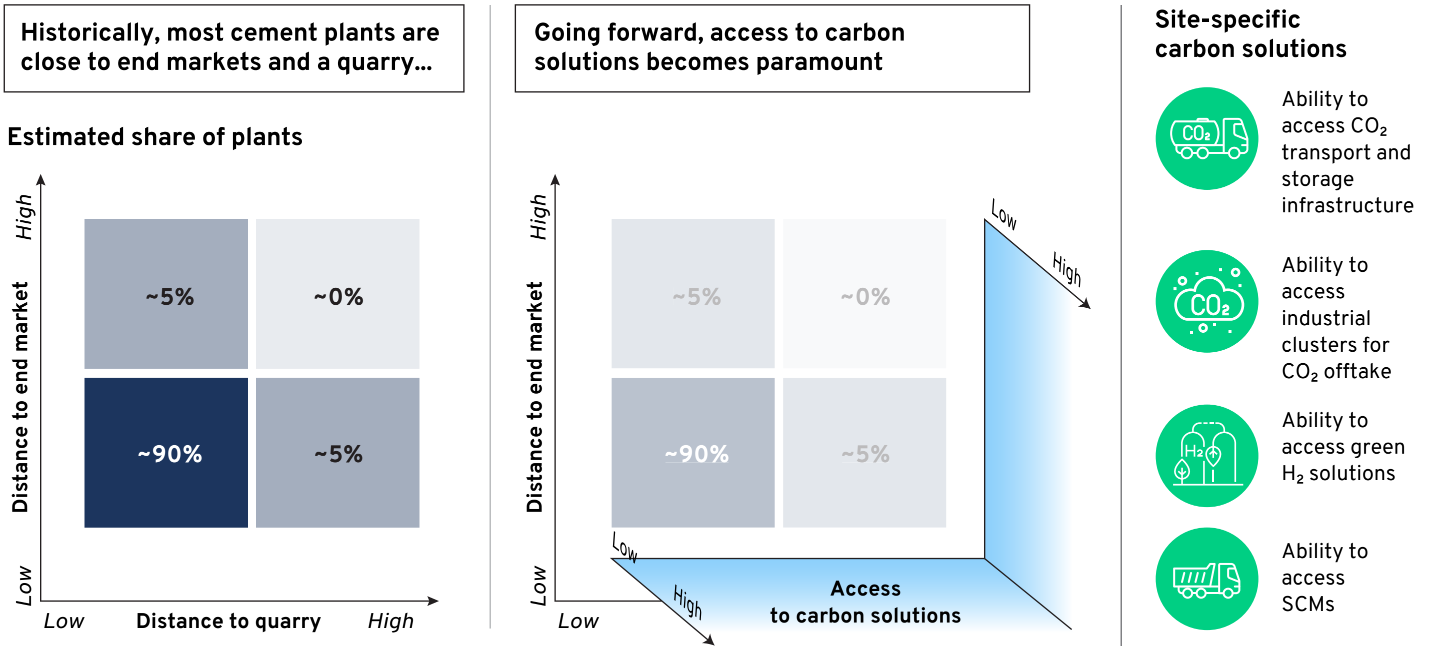
B. **Access to low-carbon energy sources,** including cheap renewable electricity or alternative fuels to heat the kilns (e.g., waste or low-carbon hydrogen).

C. **Access to carbon storage and usage infrastructure:** Although underground CO_2 storage is available in many locations, it may not be cost-effective or available to access because of long transportation distances. Proximity to an industrial hub facilitates the access to CO_2 transport and storage facilities and improves carbon capture business cases by dividing costs among users and increasing the ability to find off-takers for CO_2. In the absence of local carbon storage and/or usage infrastructure, plant owners will have to use long-distance transportation options (e.g., shipping) or decarbonise emissions with other net-zero technologies.

Long-term planning in collaboration with infrastructure providers and other materials providers is essential to ensure that the right mix of decarbonisation solutions is chosen for a specific plant and the risk of stranded assets is minimised.

EXHIBIT G

Access to low-carbon solutions will become a factor in investments decisions for new and existing plans



Source: MPP expert interviews

8. Compared with a no decarbonisation scenario, decarbonising cement and concrete production decreases investment within the sector by 7%, but total investments including the enabling infrastructure increase by 35%.[viii]

Decarbonising the sector will require changes to two types of investment:

1. **Investment in the concrete and cement sector** would decrease to approximately $1,000 billion, a 7% decrease[viii] compared with the Base scenario, which includes no major decarbonisation effort, due to large demand reductions. This decrease would be partially offset by increased investment in carbon capture equipment. Despite this decrease, investment per cubic metre would increase by 24%.

2. **Investment in enabling infrastructure** would increase by approximately $300 billion due to the scale-up of low-carbon power and CO_2 transport and storage networks. This investment would be delivered by other enabling sectors and paid for by the concrete and cement sector through operating costs (e.g., electricity prices).

Total investment is expected to increase to approximately $1,400 billion (35% more than in the Base scenario). Because a large share of these investments is related to the high projected use of CCU/S, resorting to CCU/S only where other decarbonisation options are not possible could help decrease the total investment needed.

Reaching net zero requires a transformation in investment distribution, with fewer additional plants than in the Base scenario and an increase in brownfield and infrastructure investments, such as for CCU/S and low-carbon power (Exhibit H):

A. **Demand levers:** Without demand-side decarbonisation measures, the concrete and cement sector would need approximately $1,000 billion in investment simply to meet growing demand over the next 30 years and maintain existing sites. In the Net-Zero scenario with lower concrete and cement demand, the investment in existing and new cement production capacities will be 40% lower (by $490 billion) compared with the Base scenario.

C. **SCMs:** Unlocking SCMs requires limited investment, with approximately **$30 billion** invested in new grinding facilities. These investments typically reduce operational costs.

D. **Supply-side decarbonisation:** The vast majority (**$390 billion**) of decarbonisation investments are associated with the installation of carbon capture equipment on existing cement plants, which costs an extra $150 million to $300 million per plant.[10,ix] More than 90% of existing plants require carbon capture. Up-front capital expenditures are expected to reduce over time as new capture technologies become available. If alternative low-carbon chemistries can deliver tested and commercially viable products, eliminating the need for CCU/S, capital costs could be reduced. Assuming capital expenditures of low-carbon chemistries are 20%–30% more expensive than traditional cement production,[x] then additional costs could be $60 million to $100 million per plant, significantly reducing the investment needed for new production. Switching to alternative fuels such as waste and hydrogen will require limited investment in kilns. The majority of the costs associated with kilns will be operational costs.

E. **Low-carbon power and CO_2 transport and storage infrastructure** represent an investment of **$440 billion**, dedicated to scaling carbon transport and storage networks ($175 billion) as well as low-carbon electricity and hydrogen generation ($250 billion to $300 billion).

There are significant uncertainties around these costs given the absence of large-scale deployment of decarbonisation solutions so far, and the site-specific nature of the investments that might be required.[xi]

[viii] Technological uncertainty on global CAPEX assumptions is approximately +/-30%. Taking into account site-specific variations, the uncertainty could be significantly higher.

[ix] For a typical cement plant producing 2.25 million tonnes cement per year. Lower range refers to the retrofit investments in 2030 for indirect calcination and the higher range refers to absorption and oxyfuel capture technologies.

[x] Based on expert interviews.

[xi] Inflation has not been taken into account in the figures in order to allow for a better comparison of the different investment scenarios.

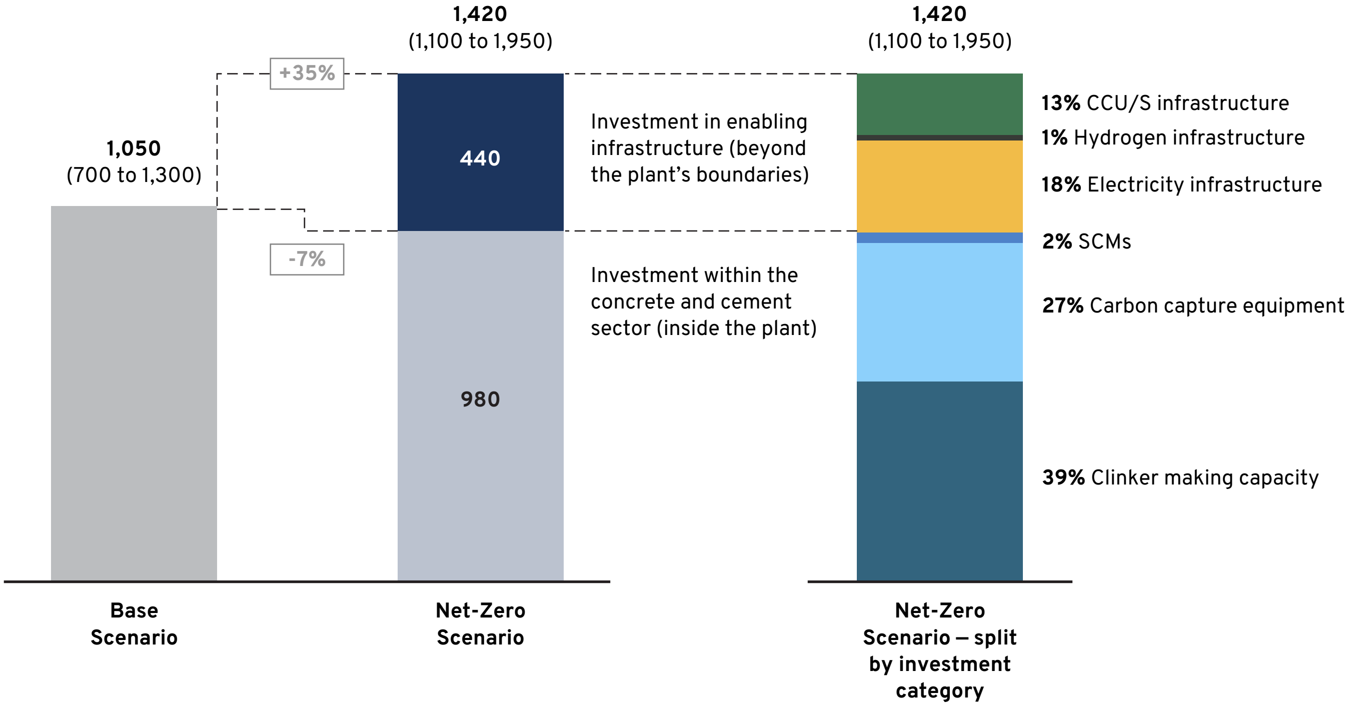
The pace of deployment of **emerging and breakthrough technologies** could impact the investment needs and operational costs of the sector. For example, alternative chemistries require new production facilities supported by increased low-carbon electricity use, which changes the investment needs in the plant and reduces the need to retrofit carbon capture equipment and access or build CCU/S infrastructure. In addition, the use of hydrogen or electricity in kilns could impact operational costs, depending on the price of locally available electricity and hydrogen.

EXHIBIT H

Delivering a Net-Zero scenario requires an investment increase of 35% against a base scenario, driven by infrastructure requirements

Cumulative investments 2022 to 2050, $ billions, mid-point

Exhibit shows mid-point values. Technological uncertainty on global CAPEX assumptions is approximately +/-30%. Taking into account site-specific variations, the uncertainty could be significantly higher.



Source: MPP analysis (2022)

9.

A cubic metre of zero-carbon concrete could cost 15%–40% more ($20–$40/m^3), a limited increase for end-users. The impact on the cost of construction is even smaller (1.5%–3% for a typical building) and could be offset by design efficiencies that reduce needed volumes.

Decarbonisation costs in the Net-Zero scenario vary from $20 to $40/$m^3$ of concrete in 2050 (a 15%–40% increase compared with today), most of which (approximately 95%) comes from the significant extra capital, operational, and transport and storage costs of carbon capture ($160–$190/t CO_2). By contrast, other decarbonisation levers (e.g., SCMs and demand reductions) can be implemented at lower or negative costs, and hence be hidden within the cost premium. The cost premium for zero-carbon concrete varies largely depending on the mix of decarbonisation levers and technology choice.

The **total green premium** (including capital and operating expenditures) **for net-zero concrete is expected to be relatively small in final projects** (increasing building construction costs by 1.5%–3%), because clinker is only a small percentage of the cost in concrete but approximately 90% of the total emissions. In addition, the clinker-binder ratio will decrease, keeping the green premium in check. Although the final cost increase for end-users is small, cement producers will need to cover significant initial investment and operating costs, including a 300%–400% increase in the cost of clinker and 40%–120% increase in the cost of cement. Innovation could reduce these investment and operating costs. Whatever the technology pathway, industry coordination and policy support are required at the production stage of the value chain to make the transition possible (Exhibit I).

The **cost of the transition for individual producers is highly variable depending on the levers used and plant locations**, which impact the starting point and combination of available decarbonisation levers as well as prices for electricity or CO_2 transport and storage. In Europe, where the transition to alternative fuels and low-carbon electricity has already made progress, average abatement costs might be greater because some of the lowest-cost decarbonisation levers have already been implemented.

The cost of the transition must also be balanced with the several revenue upside opportunities from the deployment of carbon capture and usage. These stem mostly from the sale of captured carbon dioxide to other industries (e.g., carbonation in beverages, chemicals industry, e-fuels), and the offsetting and trading of carbon, as cement decarbonisation can generate carbon credits that can be sold in carbon markets. Significant cost reduction opportunities can also be emphasised, including cost decrease from R&D and technology development as well as economies of scale, and decline in the cost of clean energy.

EXHIBIT I

Without policy support, a 40–120% increase on cement costs translates into a 1.5%–3% increase in cost of construction

Percentage cost increase

*The green premium will be higher in infrastructure projects with high concrete content and global south markets.

Note: Scenario based on the Net-Zero Scenario, using 1.6 Gt of carbon capture. Ranges driven by variation in underlying product and abatement costs. The cost premium includes capex and opex.

Source: MPP analysis (2022)

10. To stay on a 1.5C-aligned pathway by 2030, we would need greater efficiency in construction, a 5% decrease of the clinker-binder ratio and the deployment of a carbon transport and storage infrastructure serving 33-45 zero-carbon plants.

The concrete and cement value chain needs to achieve key real-economy milestones in 2025 and 2030 in order to unlock the longer-term transition to a net-zero cement and concrete industry (Exhibit J). Key priorities in this decade are the commercialisation and ramp-up of near-zero-emissions production capacity; enhanced efficiency in clinker, cement, and concrete uses; and the scale-up of the energy system infrastructure.

EXHIBIT J

Key milestones to unlock a 1.5°C-aligned, net-zero concrete and cement sector

Key milestones until 2025	Key milestones until 2030
DEMAND: Efficiency in clinker, cement, and concrete uses	
Concrete demand reduces by 4% compared with business-as-usual	Concrete demand peaks at around 38 Gt in 2030 and starts to decrease afterward
Global average clinker–binder ratio reduces to 0.61 from 0.63 today	Global average clinker–binder ratio reduces to 0.54-0.58 from 0.63 today. Regions with high SCMs availability can reach 0.5 or lower
	Share of bagged cement reduces to 20%
SUPPLY: Low- and zero-carbon concrete and cement production	
Governments permitting increased use of SCMs and use procurement power to bring about deployment	33-45 plants with carbon capture technology
Companies have developed plant-by-plant net-zero strategies	Demonstration of new technology, by implementing pilots of electric or hydrogen kilns of alternative chemistries at industrial scale
INFRASTRUCTURE: Wider energy system infrastructure	
CO_2 transport and storage plans in place and construction started across three regions	CO_2 transport and storage infrastructure operational in order to serve 33-45 plants

Source: MPP analysis

11. Reaching net zero by 2050 will require immediate action across the concrete production value chain and a portfolio of policy and financial instruments to create an enabling environment for innovation and decarbonisation.

Given the size and cost of the challenge to decarbonise the cement and concrete sector, it is essential that policymakers, finance stakeholders, and industry leaders and innovators agree now on the objective of achieving zero emissions by mid-century and act fast to implement the actions and policies needed in the 2020s to make that vision attainable (Exhibit K).

Policymakers should create an enabling policy environment through push levers, such as carbon pricing, financial support for first-of-a-kind projects, and acceleration of the standards revision process (performance-based standards and building codes). They should also use pull levers, such as embodied carbon regulations for the construction sector. In parallel, they should use public procurement to create early demand for zero-carbon cement and concrete to stimulate innovation and early action.

Industry leaders must act in collaboration across the value chain, setting up or joining industrial clusters to create infrastructure synergies and direct links between producers and off-takers of low-carbon cement and concrete. **Cement and concrete producers** must accelerate the adoption of low-carbon methods and technologies in the concrete and cement sector. **Architects, builders, and engineers** must accelerate building design best practices and optimisation of design for reducing carbon content. **Cement and concrete buyers** should then help bring those projects to market through premiums and signalling demand for material volumes of low-emissions cement and concrete through long-term offtake agreements. They also play a critical role in measuring embodied carbon and making carbon intensity a core design consideration.

Banks, institutional investors, insurers, and public-sector financial institutions must take a more hands-on approach to help manage projects and the enterprise risk and direct capital towards first-mover projects and away from carbon-intensive investments. Widespread implementation of climate-aligned investment principles will be an important first step.

Innovation can make the journey to net-zero concrete and cement faster and cheaper. Companies should continue to actively invest in R&D. In addition, support from the whole value chain and tight public/private collaboration are required to ensure that key decarbonisation technologies get past the early TRL stages and begin to scale. Innovation efforts must be complemented by de-risking mechanisms for investments (e.g., guaranties), as well as piloting and testing support.

EXHIBIT K

Key actions in the 2020s to bring the concrete and cement sector on a path to net-zero emissions by 2050

POLICY

Support:

- Implement local or regional carbon pricing with border adjustment mechanisms, targeting a minimum of $100/t CO_2 in 2030
- Introduce policy support for first-of-a-kind projects through grants, tax relief, and other forms of support

Norm revision:

- Develop stable trade- and transaction-grade standards for low emissions on low-carbon concrete
- Require systematic reporting and monitoring of embodied carbon data
- Review cement and concrete standards as well as building codes to ensure they do not prevent but rather promote innovative low-carbon design and low-carbon cement and concrete production, while ensuring safety, durability, and other key characteristics

Public procurement: Set targets for low-carbon and near-zero public procurement, progressively tightening and going further for specific large projects

Innovation support: De-risk private investments to scale carbon capture infrastructure and new technologies through project guarantees, public–private partnerships, and blended finance

INDUSTRY

Infrastructure and hubs: Set up or join industrial clusters in local areas to identify common needs and resources with other industrials (e.g., CO_2 secure storage, low-carbon power and hydrogen, sharing of industrial wastes for SCMs, and common raw materials)

Supply side:

- Set robust emissions-reduction targets that are aligned with the goal of limiting global temperature rise to 1.5°C
- Implement pilots on CCU/S in different regional contexts with new and emerging capture technology and storage and usage cases
- Engage in pilot projects to test kiln electrification and hydrogen substitution
- Demonstrate feasibility of lower clinker factors

Demand side: Allowing early offtake

- Green premiums: Agree to long-term offtake with a green premium that is proportional to production cost increment and associated risks for both supplier and buyer
- First movers, owners, architects, contractors: Commit to reducing the average embodied carbon per functional unit of concrete building and concrete infrastructure by 30% in 2030

FINANCE

Capital allocation

- Phase out capacity-maintaining investment in high-emissions technology or delayed investment
- Mobilise sufficient capital to enable at least $37 billion of additional investment in low-emissions cement and concrete production (and supporting infrastructure) each year until 2030

Business case innovation: Co-develop strategies to manage the market, credit, liquidity, operational, and policy risks for first-of-a-kind projects

Source: MPP analysis

MAKING NET-ZERO CONCRETE AND CEMENT POSSIBLE

An industry-backed, 1.5°C-aligned transition strategy

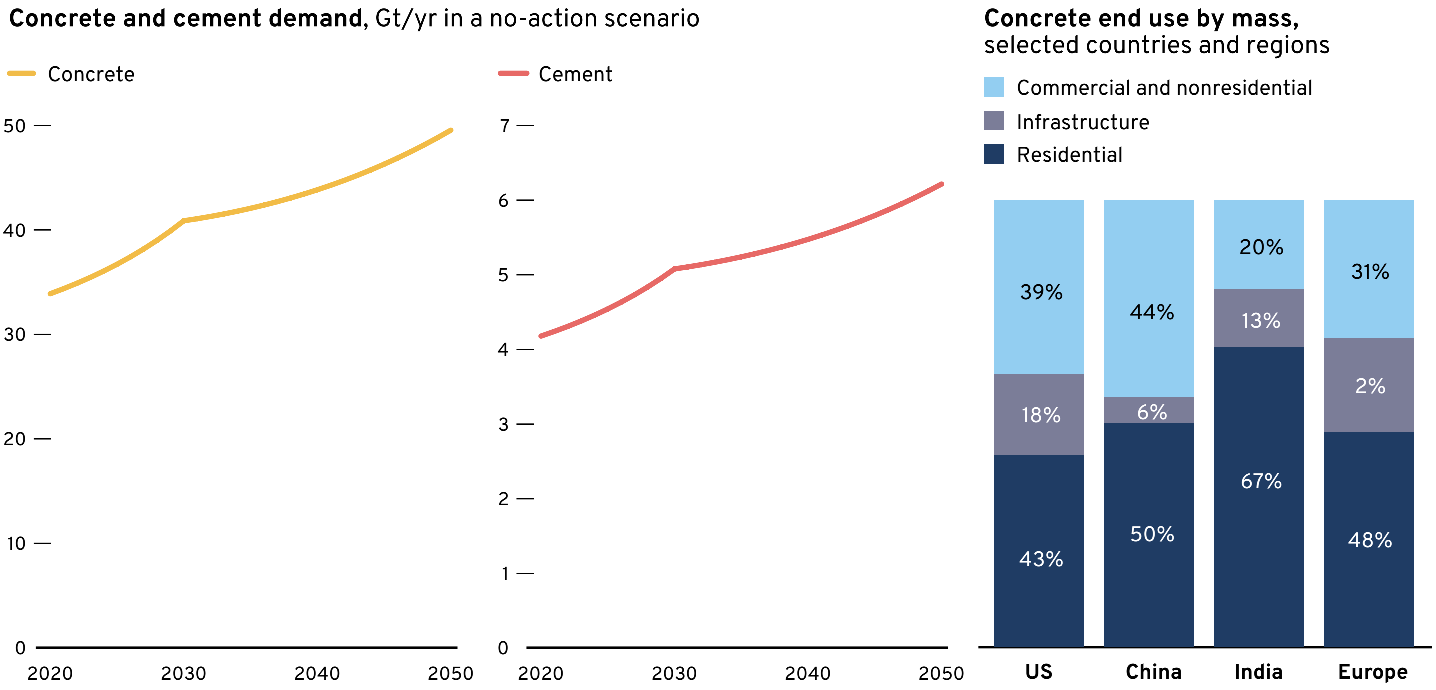
DECARBONISING CONCRETE AND CEMENT: CHALLENGES AND SOLUTIONS

1.1 Concrete, an essential but carbon-heavy material of modern life

With a global demand of 14 billion cubic metres (m^3) in 2020, concrete is the world's most widely used material after water.[11] It is an essential part of the economy, critical to buildings, transportation, and other infrastructure. Concrete is produced in bulk all over the globe. Approximately 70% of cement produced is used in concrete production, and the rest is used in mortars and plasters.[12] Key applications of concrete and cement include use in residential buildings (40%–70%), commercial and nonresidential buildings (20%–45%), and infrastructure (5%–20%).[13] Across all regions, buildings, whether residential or commercial, are the main use (Exhibit 1.1). As the need for housing and infrastructure in emerging economies continues to grow, demand for cement is projected to increase 49%, from 4.2 gigatonnes (Gt) in 2020 to 6.2 Gt in 2050, if no efficiency gains are made.[14]

EXHIBIT 1.1

Expected demand growth and end uses of concrete and cement



Concrete and cement demand, Gt/yr in a no-action scenario

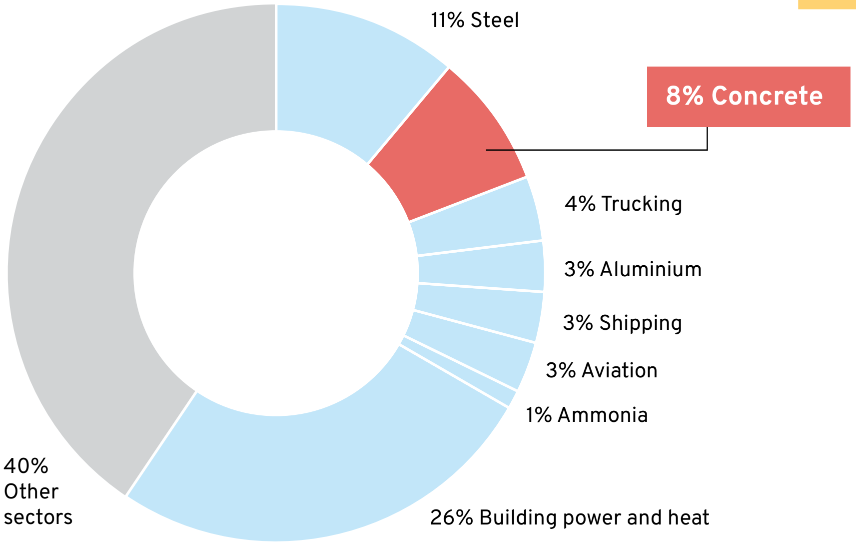
Concrete end use by mass, selected countries and regions

Source: Demand – GCCA Roadmap; end use – Material Economics Industrial Transformation 2050, Cembureau 2021 Activity Report, WBCSD Low Carbon Technology Roadmap for the Indian Cement Sector: Status Review 2018, Climate Works Decarbonizing Concrete

This expected demand increase presents a major climate impact. The concrete and cement sector already represents about 7%–8% of global CO_2 emissions (5% of all GHG emissions),[15,xii] and is the second largest emitting industrial sector after the iron and steel sector (Exhibit 1.2). Despite energy efficiency improvements, in the absence of any further action, emissions are expected to grow by about 38% by 2050, driven by increases in demand.

EXHIBIT 1.2

Concrete and cement within the context of global carbon dioxide (CO_2e) emissions



Note: Approximately 99% of the concrete and cement sector's Scope 1 and 2 emissions are CO_2; 5% of total global GHG (CO_2 equivalent [CO_2e]) emissions derive from the concrete and cement industry. Decarbonisation in the context of this strategy therefore refers to CO_2 mitigation unless otherwise stated.

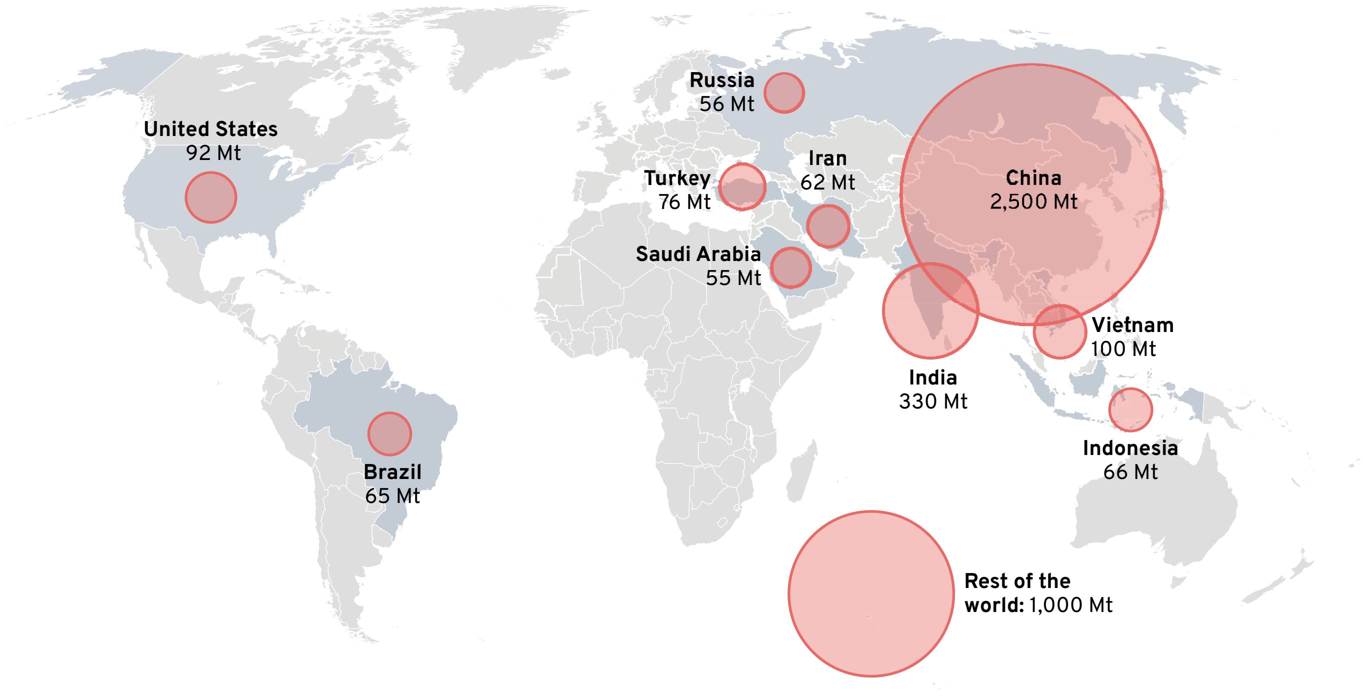
Source: IEA and MPP analysis

[xii] Process- and energy-related emissions.

Concrete and cement production is a highly localised market; plants are traditionally sited close to limestone quarries and end markets. The plants are therefore relatively distributed geographically, with the top 10 producers accounting for less than 30% of global production, and the top 100 producers accounting for 60%.[16] Concrete and cement are bulky and low-value products and are therefore seldom economical to transport over long distances.[xiii] Some 55% of global cement is produced in China, reflecting its large consumption, followed by India at 8% (Exhibit 1.3).[17]

EXHIBIT 1.3

The 10 largest cement-producing countries in 2021



Source: US Geological Survey, **https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information**

How are concrete and cement made?

The conventional concrete production cycle starts with the manufacturing of the key ingredient: clinker. Clinker is interground with other raw materials (e.g., gypsum) or blended with supplementary cementitious materials (SCMs) to produce various cement types. Cement can then be used with sand to make mortars, renders, and screeds. Or, more commonly, cement is combined with aggregates, water, and further SCMS to form concrete. **Clinker constitutes on average only 11% of the mass of concrete and 4% of the total cost, but accounts for 88% of the total Scope 1 and 2 emissions** of the concrete and cement industry (Exhibits 1.4 and 1.5).[xiv] Emissions at each stage of the value chain vary significantly at the site level, and are detailed here:

A. **Extraction and preparation of raw materials (1% of emissions):** Limestone and clay are the natural raw materials needed to produce clinker. These materials are available in sufficient quantities across the globe and are therefore locally sourced from quarries. The materials are crushed, blended, and homogenised to ensure consistent high quality. This process causes minor Scope 2 emissions and Scope 1 or 3 emissions (depending whether the quarry is owned by the cement producer) from raw materials extraction, transport of materials and equipment, and energy use for extraction, transport, and blending.

B. **Clinker production (88% of emissions):** Clinker is an intermediary product produced out of the extracted limestone and clay. This raw material mix is then heated at high temperatures to ensure it hardens with the addition of

---

[xiii] It must be noted that the increasing import of cement is why the European Union has introduced a Carbon Border Adjustment Mechanism for cement.

[xiv] Excludes reinforcement.

water (a key cement-inherent characteristic). Burning this raw material mix produces CO_2 emissions in two ways:

- CO_2 is generated by the calcination of limestone ($CaCO_3$) into lime (CaO) and CO_2. This accounts for approximately two-thirds of emissions related to clinker production and 53% of the total emissions in the concrete-making process. In this report, this part will be referred to as **process emissions**.
- CO_2 is also generated by burning fuels to reach the 900°C required for calcination and 1,450°C required for clinkerisation. This accounts for the remaining one-third of emissions related to clinker production and 35% of the total emissions in the concrete-making process. The predominant fuels currently used in clinkerisation are coal and petroleum coke (petcoke) (82%). Other fuels include natural gas (9%), industrial wastes (6%), and biogenic waste (3%). In this report, the Scope 1 and 2 emissions from burning these fuels are referred to as **energy or heat emissions**. The extraction of coal and transport of natural gas also leads to a minor amount of Scope 3 emissions.

C. **Cement production (5% of emissions):** Clinker is ground to cement in cement mills where SCMs like fly ash, ground granulated blast-furnace slag (GGBS), or limestone can be added. Emissions in this step mainly come from electricity use in grinding mills.

D. **Concrete production (5% of emissions):** Concrete is created by mixing cement, water, and an aggregate of sand, gravel, and crushed stone. This process can occur on-site (using bagged cement), in bulk at a plant that produces ready-mix concrete, or at a factory making precast products. Emissions in this step mainly come from the transportation of the materials and electricity needed for mixing.

E. **Concrete application (1% of emissions):** Concrete is then used in the construction of buildings and infrastructure. The emissions from this step come from equipment use and the equipment's electricity use and fuel emissions.

F. **Recarbonation (reduces total emissions by 10%):** Recarbonation refers to the process where CaO in cement reacts with CO_2 in the air and forms calcium carbonate ($CaCO_3$) throughout the concrete's lifetime. In other words, cement absorbs CO_2 from the air, offsetting some of the carbon emissions from its production.

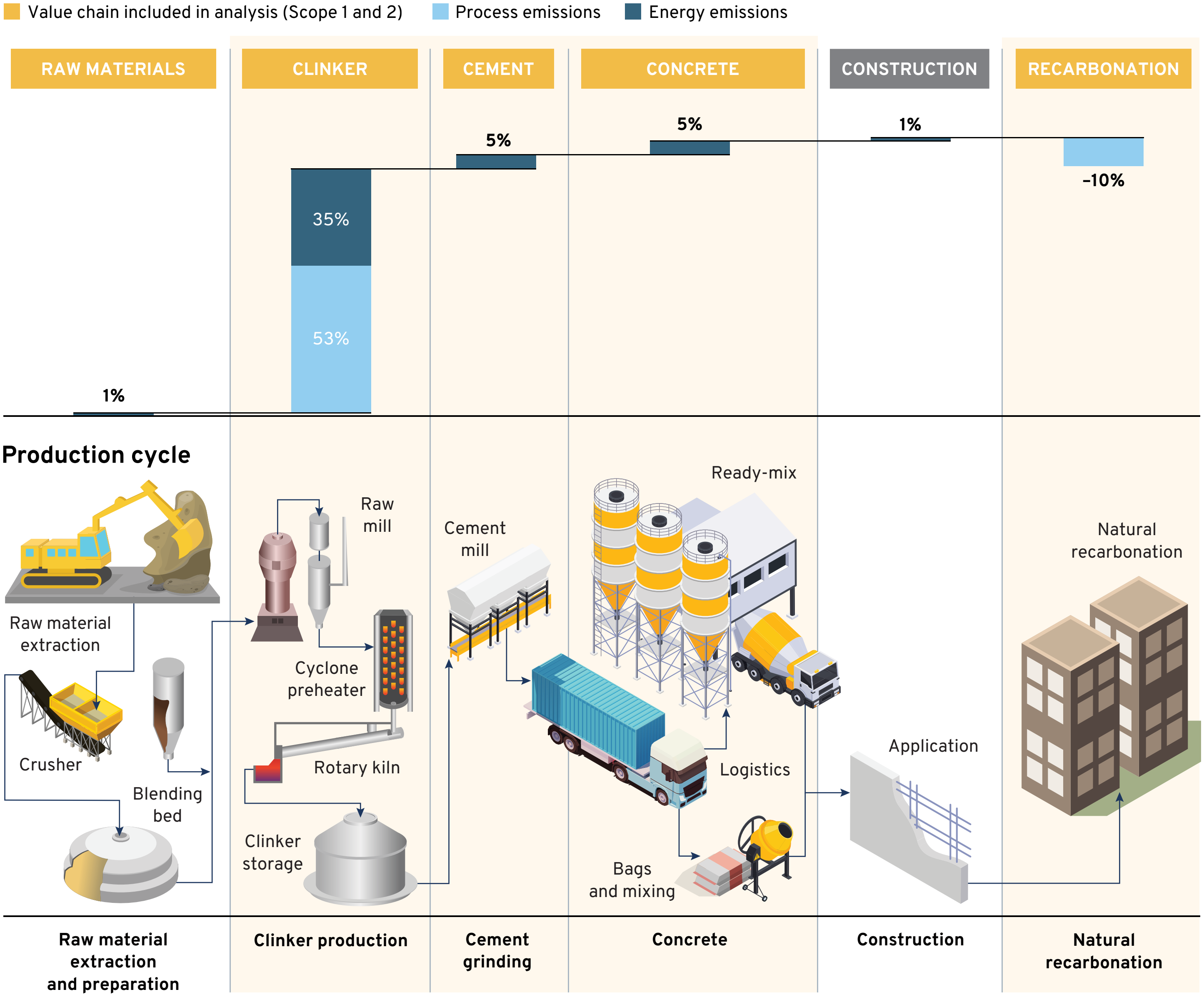
The percentage of CO_2 process emissions that is ultimately reabsorbed in a concrete product over its lifetime depends on many factors. However, across all types of concrete, a conservative estimate is 20% of the process emissions,[xv] which is equivalent to a 10% reduction in total emissions (process emissions are 53% of total emissions).

[xv] Based on the lower bound of the tier 1 CO_2 uptake model for concrete published by IVL, the Swedish Environmental Research Institute.

EXHIBIT 1.4

Emissions from the full concrete and cement value chain

Percentage of total CO_2 emissions of the concrete and cement sector

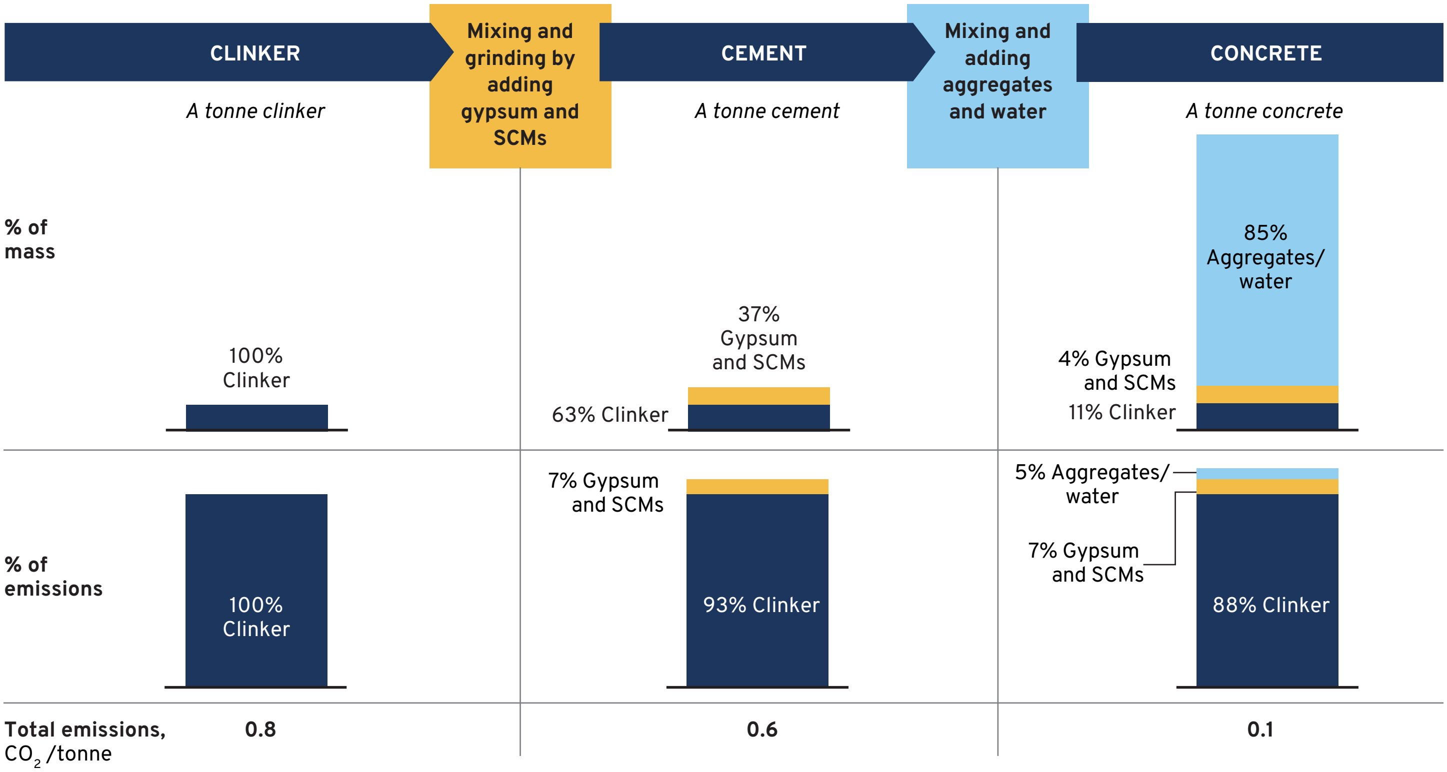


Note: This illustration covers Scope 1 and 2 emissions and includes total raw material extraction. Other construction materials are not considered in this analysis.

Source: McKinsey & Company, https://www.mckinsey.com/industries/chemicals/our-insights/laying-the-foundation-for-zero-carbon-cement

EXHIBIT 1.5

Mass of and emissions from key products in the concrete and cement value chain



Source: MPP analysis, Material Economics Industrial Transformation 2050

1.2 Why is concrete and cement production hard to decarbonise?

Although this report shows that decarbonisation is feasible, the concrete and cement sector is often labelled as 'hard to abate' for four key reasons:

1. **Process emissions from clinker production:** Today, clinker is made from a mix of two raw components: limestone and clay. The limestone calcination process generates CO_2 process emissions, which account for 53% of the sector's emissions. Because this CO_2 is released through a chemical reaction, it cannot be eliminated by increasing efficiency or changing fuel.

2. **High kiln temperature:** Thirty-five percent of the sector's emissions comes from burning fuels to reach the 1,450°C required for clinkerisation and the transformation of limestone with the other raw materials inside the kiln.[xvi] Today, commercially available kilns predominately use coal, but also biomass and industrial waste (particularly in Europe) and natural gas (in Africa, Russia, the Middle East, and North America). It remains technically challenging to fully decarbonise high-temperature heating processes.

3. **Significant projected demand growth:** Global cement production capacity increased by 30% in the last decade.[18] With no further action, demand for cement is expected to grow by 14% from 2020 to 2030, and another 22% by 2050, driven by population growth and economic development in Global South countries outside of China.[19]

4. **Highly localised market:** Concrete and cement are bulky, low-value products, rarely economical to transport over long distances. Because they are usually produced close to their use (less than 50 km for concrete and 250 km for cement), the decarbonisation of concrete and cement depends on local resources and infrastructure, with limited significant relocation of industrial sites. Region-specific decarbonisation pathways are therefore critical.

[xvi] Remaining emissions are from mining, cement grinding, concrete production, and construction.

1.3 Decarbonisation solution portfolio

This section provides a high-level overview of the available levers to get to net-zero GHG emissions by 2050, while complying with a 1.5°C carbon budget – based on the following definitions of 1.5°C carbon budget (Box 1) and net zero (Box 2). As highlighted in Section 1.1, net zero in the context of this strategy predominantly refers to net-zero CO_2 emissions, as non-CO_2 GHG emissions are limited in concrete and cement production (mostly as upstream Scope 3 emissions).

Immediate action is necessary; 2050 is just one investment cycle away owing to the industry's long-lasting capital assets (30–50 years).[20] Over the next 10 years, major new investments should be net-zero-compatible and decarbonisation technologies should be deployed on a large enough scale to trigger economies of scale and enable large-scale GHG emissions reductions in the following years.[21]

BOX 1

The 1.5°C carbon budget for concrete and cement

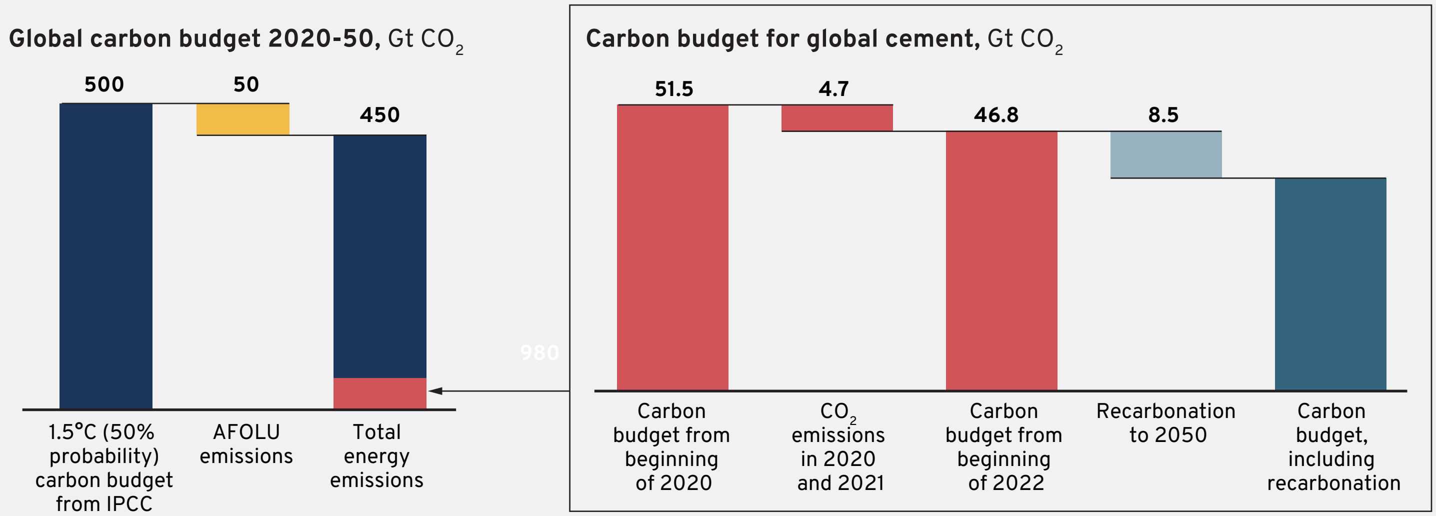
The Intergovernmental Panel on Climate Change (IPCC) estimated that in order to have a 50% chance of limiting global warming to 1.5°C above preindustrial levels, the global carbon budget from the beginning of 2020 was around 500 Gt CO_2.

Out of this budget, about 50 Gt CO_2 of net anthropogenic emissions from agriculture, forestry, and other land use are subtracted. That leaves approximatively 450 Gt CO_2 for all energy sectors that needs to be allocated to individual sectors according to their decarbonisation complexity. Hard-to-abate sectors are limited in their decarbonisation speed, whereas other sectors like power or automotive could switch to low-carbon technologies more quickly.

In a preliminary assessment by MPP, roughly 50% of the 450 Gt CO_2 has been allocated to the seven MPP sectors (aluminium, aviation, chemicals, concrete/cement, shipping, steel, and trucking). The sectoral allocation is based on the cumulative sectoral emissions from the International Energy Agency's *Net Zero by 2050* report and the One Earth Climate Model between 2020 and 2050, which serve as a proxy of how difficult it is to abate each sector.

Following this methodology, from 2022 to 2050, the global concrete and cement sector has a maximum budget of approximately 47 Gt CO_2 excluding recarbonation and 38 Gt including recarbonation. Given the variety of other potential sectoral allocation methods, this value should not be taken as the absolute truth, but rather as an indicative figure for a 1.5°C carbon budget for the concrete and cement sector.

The 1.5°C carbon budget for global concrete and cement amounts to 47 Gt CO_2 between 2022 and 2050



Global carbon budget 2020-50, Gt CO_2

Carbon budget for global cement, Gt CO_2

Note: The carbon budget of 47 Gt CO_2 is compatible with a probability of 50% to stay within the 1.5°C temperature limit. It is based on the average of the sectoral allocation of 14% of the total global carbon budget from IEA (2021) and 9% from One Earth Climate Model (2022), out of the 450 Gt remaining emissions for energy and industry and 4.7 Gt CO_2 emissions for both 2020 and 2021. Emissions in 2020 are sourced from IEA (2021). Emissions in 2021 are an average of the IEA's emissions in 2019 and 2020.

Source: ECRA[22], GCCA[23], MPP Analysis (2022), IEA, One Earth Climate[24]

BOX 2

The definition of net zero

The world needs to get to net-zero GHG emissions by 2050 to avoid the most harmful effects of climate change. Our definition of *net zero* prioritises in-sector decarbonisation, complemented by carbon dioxide removals (CDRs) in the hardest-to-abate sectors:

- **In-sector decarbonisation:** About 90%–95% of current emissions in each sector need to be reduced by in-sector measures. MPP's Net-Zero scenario looks to achieve a 91% reduction in absolute emissions compared with 2020 levels. Due to the uncertainty surrounding Scope 3 emissions, this report focuses on achieving net zero in terms of Scope 1 and 2 emissions.
- **Recarbonation:** The remaining 5%–10% of residual emissions that cannot be reduced by in-sector decarbonisation need to be neutralised by recarbonation,[xvii] which accounts for 10% of the emissions reduction in 2050 compared with 2020 levels.
- **CDRs:** If in-sector decarbonisation and recarbonation are insufficient to reach net zero, they can be complemented by out-of-sector CDRs, the potential of which is described in a recent report from the ETC.[25]

To reach net zero by 2050 and stay within the sectoral 1.5°C carbon budget, three main levers need to be pulled (Exhibit 1.6):

1. **Using concrete more efficiently,** by reducing concrete demand, implementing structural system and design improvements, extending building life spans, using alternative building materials, and reusing concrete elements. These efficiency improvements can and must be done while ensuring safe, high-quality structures. The emissions savings on a per-building basis vary between 15% and 40%, depending on the specific lever and building conditions.[26]
2. **Reducing process emissions,** by:
    - **Using less clinker per unit of cement** by replacing clinker with less emissions-intensive SCMs.
    - **Using less cement per unit of concrete** by increasing the effective strength of cement and industrialising the concrete production process. An example of industrialisation in this case refers to the transition from concrete mixed from bagged cement on project sites to concrete mixed and manufactured in ready-mix plants or in precast concrete factories.
    - **Scaling alternative low or zero carbon chemistries** (e.g., alternative binders, decarbonated raw materials). Alternative raw materials and alternative chemistries such as bio-based cement and cement made from calcium silicates may offer low-carbon alternatives to cement produced from traditional methods, replacing the need for clinker altogether. Although some solutions could already be applied,[27,xviii] further research and development is critical to further identify and scale these solutions, as on average the technology readiness level (TRL) of these alternative chemistries is comparatively low.
3. **Bringing remaining production emissions close to zero,** by:
    - **Reducing and eventually eliminating heat emissions** by deploying thermal efficiency measures and replacing fossil fuels with waste fuels, hydrogen, or electrification using renewable sources.
    - **Capturing remaining process and heat emissions** in order to store or utilise them. Carbon capture and utilisation or storage (CCU/S) should be used to capture the remaining process emissions from the calcination process as well as energy-related emissions from the use of fossil fuels and alternative fuels.

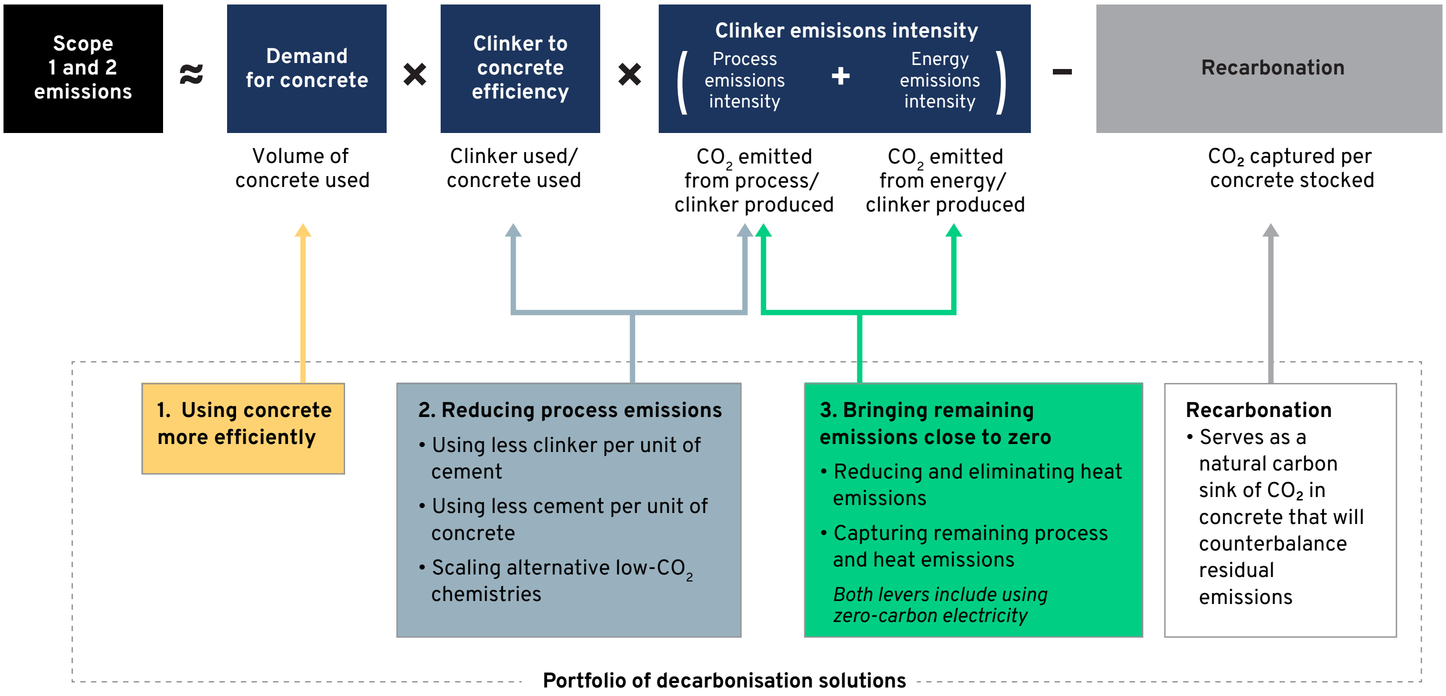
In addition, other steps within the value chain, such as power and transportation, will need to be decarbonised. Nevertheless, Sections 1.3.1, 1.3.2, and 1.3.3 focus on the three main levers, which are expected to play the largest role in decarbonising the concrete and cement sector.

[xvii] This report takes the GCCA approach to recarbonation, which in turn uses tier 1 of the carbon uptake methodology developed by the Swedish Environmental Research Institute. Further information and calculation methods can be found at **https://www.ivl.se/co2-uptake-concrete.**

[xviii] For example, geopolymers are at TRL 9.

EXHIBIT 1.6

Three main decarbonisation lever groups for the concrete and cement sector



Note: Carbon savings are relative to concrete production emissions.

Source: MPP analysis, IEA Energy Technology Perspectives 2020, Mineral Products Association, LC3

EXHIBIT 1.7

Key characteristics for each decarbonisation lever

		METHOD OF REDUCING EMISSIONS	EMISSIONS-REDUCTION POTENTIAL	TECHNOLOGY READINESS LEVEL	COST IMPLICATIONS *($/t CO_2 avoided in 2040)*	KEY BARRIERS FOR LARGE/FAST DEPLOYMENT
Using concrete more efficiently		Reduces demand for concrete	100% carbon reduction on decreased demand.	• Most methods: 9	Negative or negligible operating costs and investments.	• Consumer demand based on lack of awareness or buyer technical resources • Coordination across multiple actors in value chain
Reducing process emissions	Use of supplementary cementitious materials (SCMs)	Reduces demand for clinker	Compared with ordinary portland cement: • Fly ash: 4%-35% • Limestone: 2%–16% • GGBS: 31%–73% • Calcined clay mixed with limestone: 40%	• Existing SCMs (limestone, fly ash, GGBS): 9 • Calcined clay: 9 • Slag from new steel production methods: 3–4	-$11 to -$20/t CO_2	• Consumer demand based on lack of awareness or buyer technical resources • Standards • Local availability and production facilities
	Alternative chemistries *(decarbonated raw materials and alternative binders)*	Reduces/ eliminates emissions associated with clinker production	Up to 53% if method eliminates process emissions. Could increase if process has lower heat demand than traditional clinker making.	• Non-carbonate sources: 3 • Magnesium silicates: 3 • Raw clay: 6 • Carbonation of calcium silicates: 8	Uncertain – early estimates suggest potentially lower cost than CCU/S	• Early stage of technology development • Standards and consumer preference • Sourcing raw materials at scale
Bringing remaining emissions close to zero	Fuel switching (to waste)	Reduces emissions associated with heat for clinker production. Requires biogenic waste or CCU/S for net zero	Up to 35% if waste is biogenic or industrial waste with CCU/S (covers only heat emissions)	• Industrial and biomass wastes: 9	-$20 to -$30/t CO_2	• Permitting and regulation • Sourcing waste biomass • Combining waste with CCU/S
	Electricity/ hydrogen	Reduces on-site emissions associated with heat for clinker production	Up to 35% if electricity and hydrogen are zero carbon (covers only heat emissions)	• Hydrogen: 4 • Electricity: 4–5	Breaks even with carbon capture if electricity price is less than $32/MWh or H_2 price is less than $2.5/t H_2	• Early stage of tech. development and lack of widespread availability • High costs of hydrogen and electricity compared with coal
	Carbon capture, utilisation, or storage (CCU/S)	Captures carbon associated with clinker process and heat for clinker production, associated with storage or long-term usage	Up to 95% (depends on capture rate)	• Post-combustion: 8–9 • Oxyfuel: 6 • Indirect calcination: 7	Highly dependent on location: $160–$190/t CO_2	• Developing transport and storage and usage • Regulatory framework • High costs

Note: Carbon savings are relative to concrete production emissions.

Source: MPP analysis, IEA Energy Technology Perspectives 2020, Mineral Products Association, LC3

1.3.1 Using concrete more efficiently

The global demand for concrete construction will keep increasing to provide housing, sanitation, clean energy, and other development needs. Concrete's properties make it a versatile material, able to deliver long-lived projects that are resilient to fire, wind, water, and high-temperature events. However, many opportunities exist for construction to be delivered in a more effective manner. Increased efficiency in concrete design and construction could reduce demand for concrete by 22%, and lead to cost-effective emissions savings of 15% to 40% on a per-building basis. The reduction potential is highly variable due to different applications, regional conditions, and current levels of concrete end-use efficiency.

Exhibit 1.8 summarises the main levers that can be deployed to use concrete more efficiently and effectively, detailing their emissions-reduction potential, cost, and key implementation barriers. Most levers have high TRLs,[xix] and some can be implemented at little or negative costs (e.g., extending building life span).

Alternative construction materials for buildings, such as timber, clay, straw bale, or bamboo, can also be used in some cases instead of or in combination with concrete, although these have different performance levels. The availability of sustainably produced timber will likely constrain growth of its use in the coming decades,[28] and the use of timber is estimated to stay below a 5% market share penetration in construction materials.[29]

In addition to these levers, a decrease in the need for buildings and thereby concrete can also be achieved with a more efficient and balanced use of space, through prioritising multiunit buildings, increasing density in low-density areas (infill), and avoiding building vacancies. Redistributing space use is not only an opportunity for decreasing emissions and land use but can also improve social well-being.[30]

[xix] See the Glossary for an explanation of the TRL scale.

EXHIBIT 1.8

Non-exhaustive summary of concrete end-use efficiency levers

⬆ High cost ⬇ Low cost ◕ High amount of barriers ◔ Low amount of barriers

LEVER		DESCRIPTION	REDUCTION	COST	BARRIERS
Topology optimisation		Optimise positioning and arrangement of components to reduce material requirements	1%–3%	⬆	◑ Significant increase in construction complexity • Requires precise alignment across supply chain
Structural solutions	Precasting	Precasting in reusable mold eliminates on-site waste, improves specification accuracy	2%–4%	⬆⬇	◕ Significant storage and transportation barriers
	Post-tensioned structures	Reduce needed concrete volume by increasing strength through tensioning steel within concrete to counteract external loads of bending elements (beams/slabs)	2%–4%	⬆⬇	◔ Cultural norms of designers • Lack of training
	Voids, coffers, fill	Omit or replace concrete volumes that contribute little to structural space with fill or voids	2%–6%	⬆	◑ Increase in construction complexity
Lean design		Use automated design methods to explore options that use less material	5%–9%	⬇	◔ Reduction of rationalisation of elements (e.g., having different column cross sections adds to cost and time of construction) • Designers need assurance of quality control of construction stage • Designers/understanding from client regarding flexibility for changes
Reuse of concrete elements		Reuse concrete component parts from dissembled structures, reducing need for new concrete elements	0%–1%	⬆	◕ Significant transportation logistics • Difficulty matching supply to demand • Challenges reassessing the remaining properties of concrete
Extension of building life span		Prevent building new concrete-based structures by limiting unnecessary demolition of current stock of structurally sound assets	1%–5%	⬇	● Commercial/political interests of demolition • Difficulty assessing future architectural preferences
Alternative materials in construction		Use alternative materials in construction	Up to 5%	⬆	● Availability of materials • Achieving right structural properties

Source: UNEP[31], Material Economics[32], Ice Knowledge[33], IEA[34], Chatham House[35]

Although it is technically possible to apply most of these efficiency levers today, rapidly increasing their uptake remains challenging. Whereas some levers can be deployed by professions alone (lean design), others require coordination among project designers, engineers, and architects (structural solutions) and even involvement of the overall client (topology optimisation, reuse of concrete elements and extension of building life span, alternative building materials).

Given the low cost and high emissions-reduction potential of demand levers, it is essential to stimulate them as much and as fast as possible in the coming decade. This will require significant changes in policy, operating models, and standards setting, as well as collaboration across the value chain. This collaboration is particularly challenging given the complexity and fragmentation of the key actors who can implement design levers (Exhibit 1.9 and 1.10).

EXHIBIT 1.9

Key actors in the design lever implementation and their current roles

Client and upstream decision makers

- End investor
- Building owner
- Client
- Project manager

Client: Makes decision to invest in project; defines the scope and budget

Design team

- Architect
- Quantity surveyor
- Services engineer
- Structural engineer
- Health and safety advisor (and other consultants)

Architect: Interprets and develops the client brief; advises on sustainability and materials selection

Structural engineer: Designs the structure; specifies appropriate materials for concrete (e.g., setting performance criteria for the mix design)

Suppliers

- Contractor
- Concrete suppliers
- Cement suppliers

Contractor: Sources materials, working with the supplier to establish the mix properties to meet performance criteria

Concrete suppliers: Mixes aggregates, water, and cement and delivers resulting concrete; critical to selecting mix design

Cement suppliers: Sources raw materials and delivers cement to ready-mix plants, precast plants or project sites; responsible for majority of carbon emissions

Source: Chatham House,[36] Giesekam[37]

Barriers to uptake of concrete efficiency levers

EXHIBIT 1.10

Financial and legal barriers

- Project cost, timescales, functionality, and aesthetics are prioritised over sustainability
- Contract structures enforce hierarchies and limit information sharing
- Litigious industry environment makes pursuing novel products difficult; concerns over durability and associated liability and reputational risk
- Policy and regulatory limitations to use of novel materials

Institutional barriers

- Fragmented supply chain and ineffective integration of different actors early in the planning process
- Current standards may prevent use of certain cement types
- Conservative nature of clients and practitioners

Knowledge and perception barriers

- Perceived unreliability and risk specifically about durability
- Lack of information on performance of novel materials
- Lack of consistent and comparable methods for calculating and reporting embodied carbon
- Negative perceptions of low-carbon materials
- Perception of high cost

Source: MPP analysis

1.3.2 Reducing process emissions

Reducing the use of clinker in concrete could significantly reduce emissions from concrete and cement, as clinker production represents 88% of total sector emissions. This lever presents a large reduction potential: clinker can be used more efficiently and can, in part, be replaced with less carbon-intensive materials. Process emissions can be reduced in three ways:

1. **Using less clinker per unit of cement** by using less emissions-intensive SCMs
2. **Using less cement per unit of concrete** by increasing the effective strength of cement and industrialising the concrete production process
3. **Scaling alternative CO_2-free chemistries** (alternative binders, decarbonated raw materials)

The following subsections further highlight these reduction methods and current barriers to their uptake.

A. Using less clinker in cement by partially replacing clinker with SCMs

Clinker content in cement can be reduced by partially replacing clinker with SCMs, which reduces carbon emissions while maintaining the cement's performance. Using SCMs also reduces the volume of landfilled materials and enhances circularity, as many SCMs are industrial by-products. This lever can be actioned today, with scalable options like ground granulated blast-furnace slag (GGBS), fly ash, ground limestone, and natural pozzolans available for deployment today. SCMs that will accelerate the transition to net zero include existing mature solutions as well as emerging ones (Box 3).

BOX 3

Examples of SCMs and their emissions-reduction potential

Some SCMs are commercially deployed today, whereas others are at a testing stage. Key SCMs of interest are highlighted below:

A. **Fly ash** and **GGBS** dominate the SCM market today. Fly ash is sourced from coal power plants (and hence has a particular benefit in high coal-consuming regions like India and China) and GGBS is sourced from blast furnaces. Their supply is expected to fall as coal and blast furnaces are phased out,[xx] but large stockpiles will allow them to continue playing a role in the short and medium term in some regions.

B. **Ground limestone** is commonly used in Europe and has, for example, recently and rapidly reached an average of 10% of cement content in North America, demonstrating potential for other markets.

C. **Natural pozzolans** can be used as an additional SCM in areas where they are abundant (e.g., volcanic regions), but their availability varies significantly by region.

D. **Calcined clay** is also a proven SCM, expected to increase significantly given its global availability. Its use is currently transitioning from the pilot stage to achieving commercial readiness in this decade.

E. **Recycled concrete fines from construction demolition wastes** are being explored as an emerging SCM, but new policies, standards, and regulations are required to make the business case profitable.

F. **Biomass ashes and silica fumes** have already been developed but are not deployed at the scale of mainstream SCMs.

The exhibit below shows the emissions-reduction potential for selected SCMs and their potential clinker-binder ratio compared with ordinary portland cement.

Emissions reduction for individual types of SCMs

EXAMPLE SCM TYPE	SCM CONTENT	SAVINGS COMPARED WITH PORTLAND CEMENT (95% CLINKER)
Fly ash (CEM II/A-V/B-V)	6% to 35%	4% to 35%
GGBS (CEM III)	36% to 80%	31% to 73%
Limestone (CEM II/A-LL)	6% to 20%	2% to 16%
Pozzolan (CEM IV)	36% to 55%	34% to 56%
Calcined clay (example LC3)	30% calcined clay 15% limestone	Approximately 40%

Note: Emissions reduction compared with ordinary portland cement with 95% clinker content. SCM content taken from standards and widely used combinations in the UK.

Source: Mineral Products Association (2019), LC3

[xx] New GGBS supply is expected to fall 80%–100% as the steel industry switches to alternative technologies (MPP Steel Sector Transition Strategy).

The global average clinker-binder ratio is currently 0.63,[xxi] with regional values ranging from 0.53 to 0.96 owing to local preferences and raw material availability. GCCA analysis shows that reducing the global average clinker-binder ratio to 0.52 could increase the volume of SCMs used by 26% in 2050 and deliver a 5%–15% reduction in costs and 18% cumulative emissions savings by 2050 (Exhibit 1.11).[xxii] Lower clinker-binder ratios and greater emission savings are possible through SCMs such as calcined clay.[38] The carbon savings that can be achieved from SCM use depends on three factors:

1. **The level of current SCM use,** which differs between individual plants/regions, depending on the cost and accessibility of SCMs. A 95% clinker content is common today for ordinary portland cement, the 5% remaining being gypsum.
2. **The emissions associated with the use of SCMs,** as some SCMs, such as calcined clays, require additional grinding or calcination, which requires electricity use and produces additional emissions.
3. **The levels of clinker-binder ratio** that can be achieved, depending on the desired properties of the cement, which is dictated by standards in most countries.

[xxi] Clinker-binder ratio demonstrates the amount of clinker used in cement. Binder means all material in concrete, such as cement, fly ash, GGBS, and limestone fines.

[xxii] The value 0.52 is taken as an illustrative example. Regional variations range from 0.47 to 0.55 in MPP's Net-Zero scenario and from 0.42 to 0.49 in the Rapid Barrier Elimination scenario.

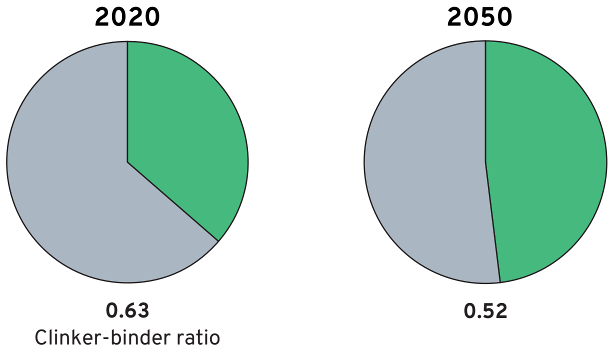
EXHIBIT 1.11

New SCMs can play a significant role in 2050 and reduce emissions by 18% in 2050 and costs by 5%–15%

SCMs can reduce emissions per tonne by 18% and costs by up to 15% in 2050 ...

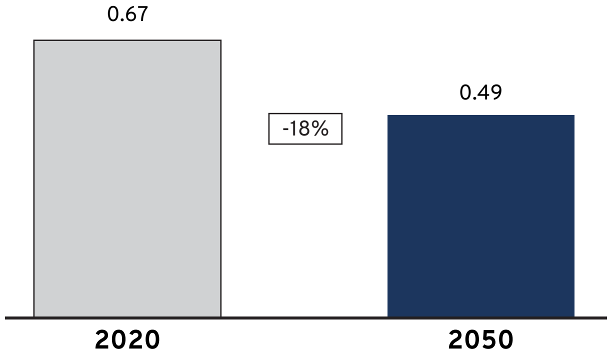
CEMENT COMPOSITION

Average cement mix ▨ Clinker 🟩 SCMs



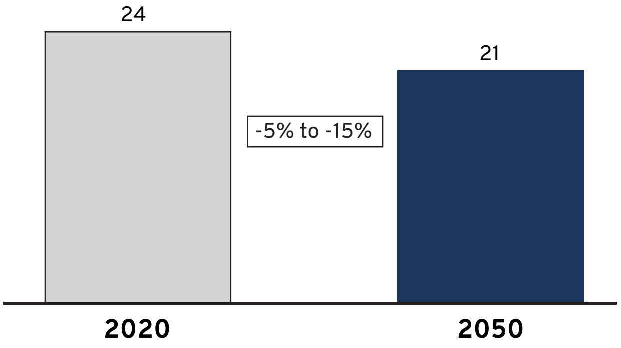
EMISSIONS

t CO_2/t cement, based on low-carbon SCMs



COSTS

$/t cement, cost reductions depend on SCMs used



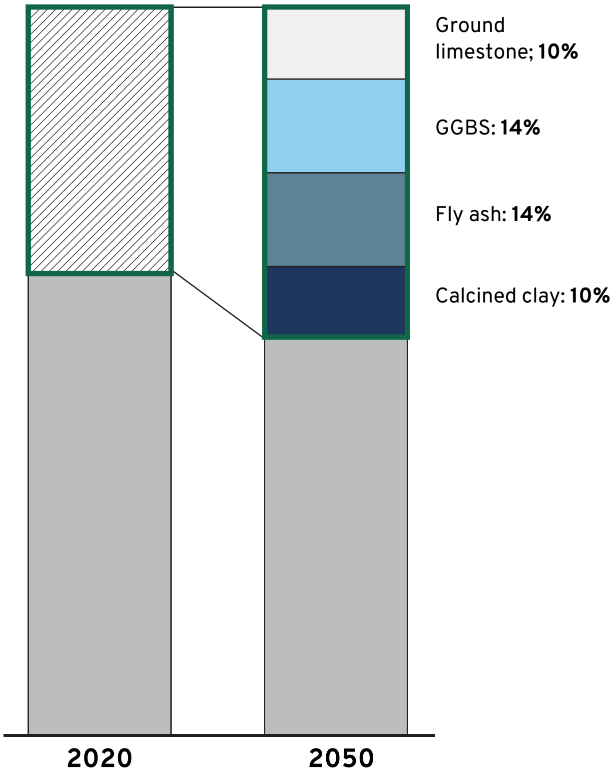
Note: SCM availability is on a global level compared with limestone.

Source: GCCA clinker substitutes, ECRA,[39] MPP interviews with experts

... and they are expected to increase by 26% in volume by 2050

GLOBAL CEMENT MIX

% of mass



AVAILABILITY OF SCMs

	Present	2050
Ground limestone	High	High
GGBS	High	Low–Medium (higher in developing economies)
Fly ash	High	Low–Medium (higher in developing economies)
Calcined clay*	High	High
Others	-	-

*While Calcined clay raw materials are widely available, the SCM needs to be complemented with real-world production capacity

The applicability of SCMs to cement depends on a variety of technical factors, including (1) the strength needed for the specific application of concrete and cement, (2) the durability effects of SCMs on concrete, and (3) the workability of the concrete mix (e.g., some SCMs can make concrete more ‘sticky’). Chemical admixtures, added during concrete mixing, could mitigate these limitations, enhancing specific properties of concrete and enabling a higher usage of SCMs. SCM producers claim today that admixtures could reduce the clinker content to 20%, blended with low-carbon SCMs and fillers.[40] Depending on the admixture, the percentage may vary significantly.

However, the primary barriers to further uptake of SCMs are not technical. SCM uptake depends on client/project team specification and regulatory standards. The latter should be amended to not just permit, but to promote wider use of SCMs. Local availability of SCMs is also a key constraining factor, as SCMs are bulk materials and are therefore locally and regionally sourced. Requests for low or no SCM content are often technically unwarranted and based on reuse of previous projects’ specifications or lack of awareness or resources. Section 3 explores the required actions to accelerate SCM adoption, in particular through updating existing standards, developing performance-based standards, and using public procurement.

B. Using less cement in concrete through a more efficient mixing of cement and industrialisation

It is possible to use less cement in concrete by improving mix design, grading aggregates better, using admixtures more effectively, and improving quality control, resulting in a lower use of clinker. The industrialisation of concrete production facilitates this higher material efficiency through the shift from **bagged cement** (mixed on-site) to **bulk cement**.

- **Bagged:** Cement is supplied in bags as dry cement and mixed on-site with aggregates and water. Bagged cement makes up 42% of the market share today.[41]

- **Bulk:** Cement is mixed into concrete at a ready-mix plant or precast factories and transported to site as wet concrete. Bulk cement makes up 58% of the market share today.

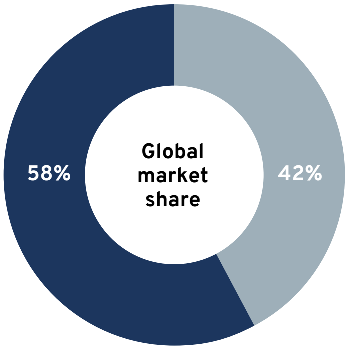
As Exhibit 1.12 illustrates, industrialised processes often adhere better to mix specifications, whereas overspecification in bagged cement usage is more common. Reduced clinker intensity through industrialisation alone is said to reduce wastage by at least 20% to 30%.[42]

Because 42% of the global cement market is bagged, the potential to decrease overapplication of clinker is large. The use of bagged cement is prevalent in emerging markets, where government policies may not encourage cement industrialisation and projects tend to be small and may therefore not have access to bulk cement. For example, 70% of cement in Brazil is sold in bags, compared with 5% in the United States.[43]

EXHIBIT 1.12

Properties of concrete made from bulk versus bagged cement

MADE FROM BULK	BAG CEMENT
More precise mix specifications	Overspecification common
Quality control	Contamination of aggregates
Better grading of aggregates	Nonoptimal grading of aggregates
Use of dispersants and admixtures	Lack of dispersants
Low binder and CO_2 intensity	High binder and CO_2 intensity



Source: Material Economics,[44] UNEP[45]

Several economical and regulatory barriers limit the uptake of industrialised processes of cement (e.g., ready-mix and precast). To overcome these barriers, policymakers should look to identify and reform restrictive construction codes hindering decarbonisation in large projects. Additionally, education efforts must target local masons and contractors, who are often unaware of the environmental implications of cement use, how to optimise materials use, and reduce their projects' carbon footprint. Governments could also provide incentives to support the transport, storage, and other infrastructure needed for bulk cement and ready-mix concrete. For example, in the Brazilian tax structure, concrete mixing at the construction site is considered a service that is taxed less (2% to 5%) than industrialised products (15% to 23%). Addressing this differential tax treatment could reduce the cost differential.

C. Scaling alternative low- or zero-carbon chemistries

In the medium to long term, process emissions within a plant could be reduced significantly if alternative chemistries break through. However, the 2050 emissions savings potential of these technologies depends on their development and deployment, which are at an early stage. These technologies produce cement without the emissions-intensive limestone calcination process and can typically address the emissions generated by the clinker-making process.

Alternative chemistries include two main categories:

1. **Alternative binders: producing low-carbon alternatives to portland cement (e.g., belite-rich clinkers, calcium sulphoaluminate, alkali-activated materials, and bio-based cement).**

   Comparable information on the cost and performance of different low-carbon alternatives is not widely available. A key next step is to have evidence of their whole life emissions and to ensure these emissions, the performance and the limitations can be compared consistently.

2. **Breakthrough chemistries and processes: producing an end product with the same chemistry and performance as portland clinker (now used as a cement binder) from decarbonated raw materials (e.g., calcium silicate, magnesium silicate, crushed concrete waste, mining tailings, and steel slags).**

   Exhibit 1.13 highlights examples of innovative solutions in alternative chemistries. These products have different levels of technology readiness, availability, and costs. Some, such as belite clinker, have entered the market but have limited emissions savings. Others, such as cement produced from calcium silicates, could achieve net-zero emissions but have not yet reached commercial readiness.

EXHIBIT 1.13

Non-exhaustive summary of innovative solutions in alternative chemistries

↑ High cost ↓ Low cost ● High availability ◔ Low availability

		Process emissions intensity, tCO_2/t binding material	Required temperature, °C	Raw materials availability	Costs relative to portland cement	Considerations
Ordinary Portland Cement from limestone (Range based on portland cement to 50/50 SCM to clinker ratio)		0.27-0.54	1,450	● Limestone		
Limited emissions saving and considerations on availability	**Belite clinker**	0.50	1,350	● Limestone	↑ Thermal energy savings but rapid cooling required	• Low heat of hydration makes useful for mass applications
	(Belite) calcium sulphoaluminate clinker	0.30-0.40	1,250	◔ Bauxite and sulfates	↓ Lower thermal energy and grinding needed	• High early strength • Reduced drying-shrinking cracking
	Calcium sulfoaluminate cement	0.30-0.40	1,200	◔ Bauxite and sulfates	↓ Lower thermal energy and grinding needed	• Reduced early strength but improved long-term strength
	Alkali-activated binders without slag	0.05-0.52	Low temperature	◔ Varies (usually industrial by-products like fly ash)	↑ Cost of raw material and activators	• Poor workability • Potential for high early compressive strength
Low maturity	**Magnesium silicate clinkers**	>0	650	◔ Magnesium oxide	↑↑ Raw material cost	• Poor workability • Potential for high early compressive strength
	Reactivated $CaCO_3$	0	1,200	● Limestone	↑ Additional processing	• Reduced reactivity compared with clinker • Process emissions stored in material • Energy emissions similar to clinker
	Calcium silicates	0	1,200	● Calcium silicate rock	↑ Additional processing	• Raw material is leached with (recycled) acid • New equipment is needed

Note: Availability based on mining operations for raw materials on a global level may vary at local level. Some cost increases can be partially offset by selling SCM that occurs as a by-product of production.

Source: Material Economics Industrial Transformation 2050, CSI ECRA Technology Papers 2017, Geopolymer Solutions Green Concrete, SSRN Cost Analysis of Geopolymer Concrete Over Conventional Concrete, IEA Technology Roadmap Low-Carbon Transition in the Cement Industry, MPP interview with experts about the value chain

If alternative chemistries can deliver on the early developers' views of cost and performance indications while respecting required safety and durability, then they could play a valuable role in reducing clinker use or reducing the carbon intensity of clinker production. Niche markets such as nonstructural components in construction could constitute a viable market-penetration route for these new cement products. Performance-based concrete and cement standards are crucial in the deployment of cement with new chemistries. R&D support on new testing methods will help accelerate the adoption of new performance-based standards. In addition, blended finance between government, private sector, and industry players will be helpful to address the first-mover risks among the potential off-takers.

1.3.3 Bringing remaining production emissions close to zero

Even if concrete is used more efficiently and less clinker is used in concrete, there remains a need to bring remaining production emissions close to zero. Two large sources of total concrete and cement CO_2 emissions come from the clinker-making process: (1) 53% of CO_2 emissions are generated when limestone ($CaCO_3$) converts to lime (CaO) during clinker making (i.e., process emissions); and (2) another 35% of CO_2 emissions come from burning fuels to reach the 1,450°C needed in the kiln to allow the clinkerisation process (i.e., energy or heat emissions).

This section focuses on two key actions needed to fully decarbonise the clinker-making process:

1. **Reducing and eventually eliminating heat emissions,** by:
    a. Deploying thermal efficiency measures
    b. Replacing fossil fuels with waste fuels, hydrogen, or electrification
2. **Capturing remaining process and heat emissions**

A. Reducing and eventually eliminating heat emissions

Heat- or energy-related emissions can be reduced through energy efficiency improvements. They can also be eliminated by replacing the fossil fuels used for heating with low- or (net) zero-emissions fuels. This section focuses on both of these levers.

Deploying electrical and thermal efficiency measures

Energy efficiency improvements have a large potential. Switching from the least efficient to the most efficient kiln can reduce the thermal energy consumption of an individual kiln by more than 40% through the deployment of three levers that reduce energy use:[46]

1. **Replacing wet kiln technology with dry kilns** can halve thermal energy requirements. MPP's Net-Zero scenario assume that the few existing wet kilns will all be replaced by 2050.

2. **Deploying waste heat recovery** to produce electrical energy could lead to electrical energy use reductions of 8%–20% in an example plant.[47,xxiii]

3. **Switching to more efficient grinding** could lead to a 10%–20% reduction in the energy used for grinding.[xxiv]

These energy efficiency levers are broadly cost-effective, with paybacks determined by each plant's setup. Because energy is a key cost driver in clinker making, these levers are expected to be deployed even in a no-decarbonisation scenario. The sum of these levers is expected to decrease the energy intensity of concrete production by 12% by 2050. This percentage is relatively low as some plants are already operating close to optimum efficiency. For instance, China, the European Union, and India are ahead of other regions in cement energy efficiency performance, with relatively new cement plants equipped with advanced energy efficiency technologies.[48] In other regions, the deployment of energy efficiency levers may be hindered by significant barriers or competing investments. To overcome these barriers, governments could incentivise the cement industry further through mandatory emissions targets and market-based mechanisms. For example, India's Perform, Achieve, Trade scheme tries to achieve energy efficiency improvements through a cap-and-trade system.

Replacing fossil fuels with waste fuels, hydrogen, or electrification

Even with energy efficiency improvements, the energy used for the remaining heating has to be decarbonised by mid-century. The need to decarbonise fuels is significant as the energy currently used to heat kilns produces 35% of the sector's emissions. The predominant fuels currently used to heat kilns are coal and petcoke (82%). Other fuels include natural gas (9%), industrial wastes (6%), and biogenic waste (3%).

Heat energy can be decarbonised through the use of low- or zero-emissions fuels, including nonreusable nonrecyclable waste streams (available now) and hydrogen and electrification (which both require innovation and cheap, abundant zero-carbon electricity to reach cost-

---

[xxiii] Based on the electrical energy consumption of a reference clinker kiln of 102 kilowatt-hour per tonne clinker.

[xxiv] Depending on the fineness of the clinker and the SCM required for the respective cements. New gas cleaning equipment and automatisation will also require additional energy.

competitiveness). A 'decarbonised world' can also be achieved by capturing the energy-related emissions through CCU/S (further highlighted in Section 1.3.3B). However, replacing some or all of the fossil fuels or electrifying kilns would reduce overall CCU/S requirements. This in turn would create a largely fossil fuel–free production process and increase system efficiency (process emissions tend to have a higher CO_2 concentration than energy-related emissions, reducing the need for and costs of CCU/S). Of these low- or zero-emissions alternatives, alternative fuels (i.e., waste, hydrogen) or electrification could be key energy sources:

- **Using waste from biological or industrial origins (used as an alternative fuel):** Wastes can be combined with fossil fuels to produce 'alternative fuels.' This report considers two archetypes of these mixes: a blend with 43% energy content from waste (14% biomass and 29% industrial waste) and a blend with 90% energy content from wastes (32% biomass and 59% industrial waste).[xxv] The mix depends on local conditions and long-term availability of wastes.

  Kilns using waste from biological or industrial origins reduce emissions and costs and increase circularity by preventing waste from going to landfills or being incinerated. The mineral content from waste can also reduce the raw materials needed in clinker production through co-processing. The technology is ready and widely used in Europe. The share of waste as fuels (i.e., waste of fossil origin and biogenic waste) in cement kilns is forecast to increase from around 6% today to around 40% by 2050. However, the mix of waste is vital in determining its role in the transition, as some combinations can increase emissions compared with coal (Exhibit 1.15). If waste is not fully biogenic, carbon capture is still required to lower emissions to a net-zero pathway, offering the possibility of negative emissions on the biogenic share. Emissions of non-CO_2 air pollutants must also be subject to emissions control measures and monitoring to enable the safe treatment of waste.[49]

  The availability of feedstock waste depends on the waste management practices in different regions. Where waste management practices are developed, there can be good availability of high-quality and low-cost waste. For example, in Europe, waste represented over half of the energy input in kilns in 2015, half of which was plastics and industrial waste.[50] Over time, the availability of applicable waste might increase, although waste streams could also decrease due to increased recyclability by mid-century.

  Alternative ways of accounting for emissions from wastes are outlined in Box 4.

  Burning waste presents the benefit of reducing emissions today with a technology-ready solution, as well as participating in the decarbonisation of the waste sector. It can be complemented or replaced by other net-zero solutions such as low-carbon electricity and hydrogen as they become available.

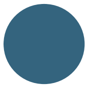
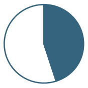
- **Low-carbon hydrogen (used as an alternative fuel):** Several studies (e.g., BEIS, Mineral Products Association[51]) showcase how hydrogen can be mixed with waste and other fuels to heat kilns. In the future, hydrogen could also be used as the sole fuel to heat kilns (Exhibit 1.14). However, some technical barriers first need to be addressed. For example, research is needed to determine the effect of hydrogen-based flames on cement properties. Financially, the use of hydrogen is expected to become cost-competitive if and where low-carbon hydrogen costs are less than $2.5/kg (Box 5). This price is closely linked to the price of renewable electricity as hydrogen kilns come with significant energy requirements. If hydrogen replaced 10% of the total energy needed for heating, hydrogen demand would increase by 6 megatonnes (Mt), representing approximately 1% of 2050 forecast global hydrogen demand.

[xxv] Shares of alternative fuels are based on expert review from ECRA. The mix will vary significantly on a plant-by-plant basis. For example, with high availability of local waste biomass, an individual plant may source most of its energy from biomass.

Emissions savings and availability of waste and hydrogen as alternative fuels

EXHIBIT 1.14

🟥 Increased emissions 🟩 Decreased emissions ● High uncertainty ○ Low uncertainty

Alternative fuels		Main benefit of co-processing	Considerations	Difference in emissions, including biogenic fraction, kg CO_2/GJ	Difference in emissions, kg CO_2/GJ	**Abundance of supply**, level of uncertainty depending on region
Mixed waste used in model	**Industrial waste**	• Manage non-recyclable waste that would otherwise be landfilled • Fuel cost reduction	• Nonrecyclable pure fossil waste streams from industrial origin • Recyclability of waste streams expected to increase toward 2050	🟩 -13 Industrial waste as listed in GCCA CO_2 and Energy protocol v3 (reference number used in MPP model) ▨ -13 to +47 Industrial waste – Varied sources (not meeting GCCA CO_2 and Energy protocol v3 standards)		
	Treated municipal waste		• Nonrecyclable streams with a mixture of animal bone meal and fats, solvents, and/or impregnated sawdust	🟩 -3	🟩 -17	
Green H_2		• Eliminate fuel emissions	• Green H_2 can be competitive in regions with low cost and abundant renewable energy • High shares of H_2 co-firing may require significant retrofits • Use should be prioritised for sectors where green H_2 will have a stronger abatement impact	🟩 -96	🟩 -96	

Note: Emission intensity of industrial waste varies due to origin, geography and composition, with a range of -13 to +47 kgCO2/GJ, but sourcing and processing can ensure bottom of this range and hence emission savings are achieved. GCCA CO2 and Energy protocol v 3 should be adhered to in relation to alternative fuels.

Source: GCCA,[52] IPCC[53]

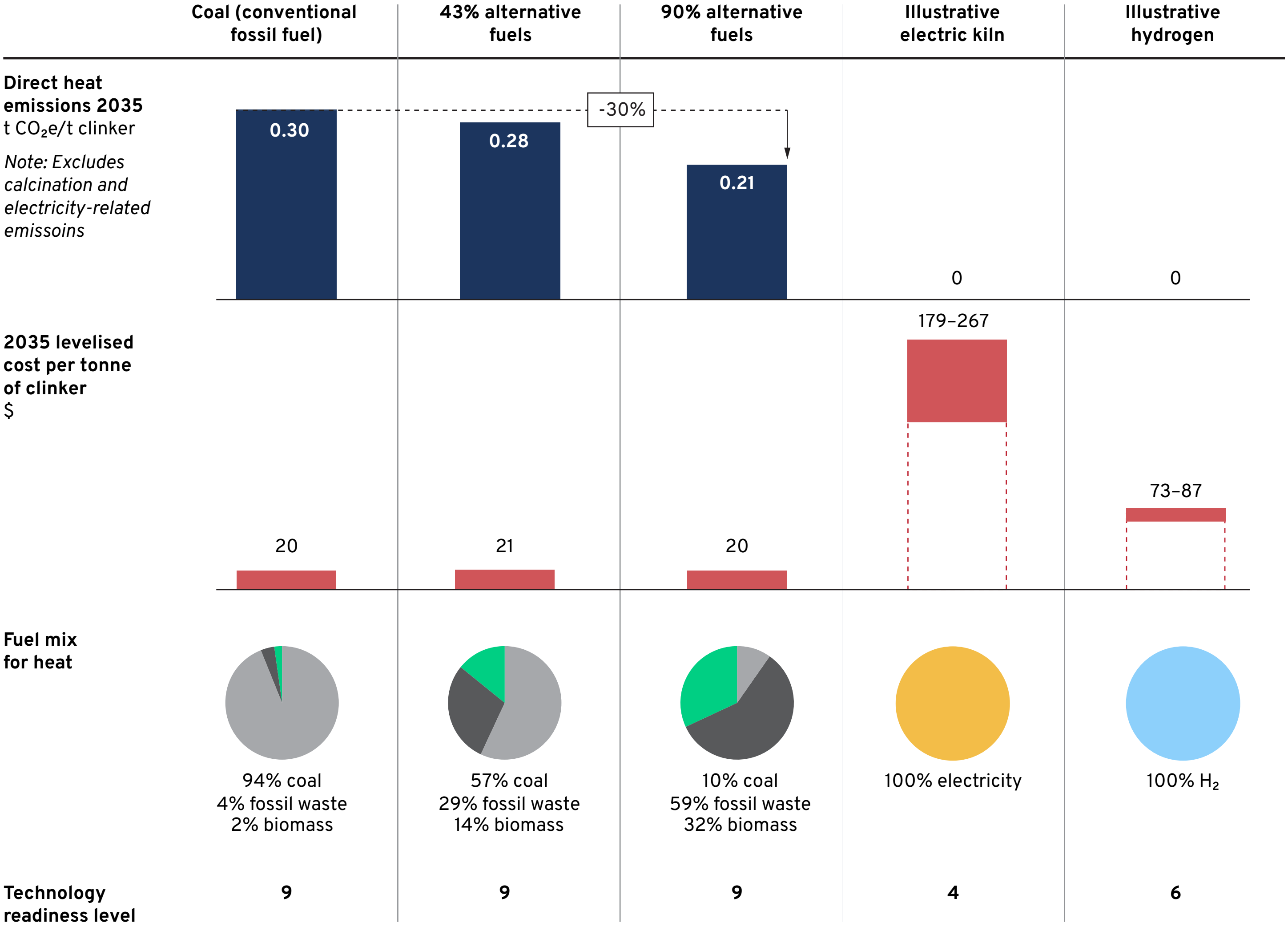
- **Kilns might be partially or fully electrified, using zero-carbon electricity:** Technologies to electrify kilns are at an early stage of development with a TRL of 4. Significant development is therefore required for these technologies to develop from being lab-validated to being commercially available at scale. Electricity heating elements, such as plasma torches, also require further development to prove and ensure robustness. Additionally, electrification is only expected to be competitive and scalable in locations with abundant low-cost low-carbon power as the energy requirements are significant: replacing 10% of the total energy demand for the sector with zero-carbon electricity would represent a zero-carbon electricity demand of 550 terawatt-hours (TWh) (0.5% of projected total global electricity supply in 2050). To compete with CCU/S for heat, electricity should generally be available for less than $32 per megawatt-hour (MWh), though this will vary depending on local costs (Box 5).

Exhibit 1.15 further summarises the potential of using waste, hydrogen, and electricity as near-zero-carbon energy sources to decrease energy-related emissions. How a plant owner chooses to decarbonise heat emissions will depend on local availability and pricing of zero-carbon energy sources. As these technologies only decarbonise energy emissions, they will need to be used in addition to decarbonisation options tackling process emissions, hence adding to the total decarbonisation cost. In the short term, technology-ready solutions (e.g., use of waste) are the most cost-effective choice and could result in an 11% decrease in energy-related emissions. However, as net zero becomes the objective, these technologies might be replaced or complemented with full-decarbonisation options like carbon capture for process and heat emissions or coupled with other technologies such as low-carbon hydrogen. The use of hydrogen or electric kilns has the promise of a purer CO_2 stream from process emissions only, resulting in cheaper carbon capture. However, given the TRL of 4 and 6 for electric kilns and hydrogen, respectively, more R&D is needed for these technologies to achieve high market penetration.

Governments could play a key role in developing these technologies as they could encourage R&D of hydrogen and electrification projects through regulatory and fiscal incentives such as grants, tax breaks, and loan programmes. Governments could also set clean energy adoption targets for the cement industry or initiate mandatory coal phaseout time lines.

EXHIBIT 1.15

Comparison of conventional and near-zero-emissions cement heat technologies



Note: The timing for commercial availability of hydrogen and electric kiln is uncertain. The retrofit capital expenditure for electric kilns is assumed to be $24 million/kiln (RMI) with a kiln production capacity of 4,000 tonnes of clinker/day. No retrofit capital expenditure or energy penalty for the hydrogen kiln is assumed. Range of levelised cost per tonne of clinker depends on electricity and hydrogen prices (more details in Box 3) The emissions analysis excludes the process emissions of clinker production.

Source: MPP analyses, RMI (2022),[54] ECRA (2022)[55]

BOX 4

Gross and net emissions from industrial waste

The Cement CO_2 Protocol v3.0 (2011) defines two ways of accounting for emissions:[56]

- **Gross emissions** are the emissions from the kiln itself and the direct emissions from burning fuels such as coal, wastes, or natural gas, with bio-based wastes counted as emitting zero emissions.
- **Net emissions** are the gross emissions minus the landfill or incineration emissions avoided by the alternative use of non-biogenic waste.

The GCCA roadmap uses the net emissions accounting method, whereas the SBTi targets use gross emissions. In line with SBTi targets, MPP's Concrete and Cement Sector Transition Strategy uses gross emissions accounting. If the emissions associated with fossil fuel waste were considered net zero through a net accounting method that recognises avoided emissions in another sector (a concept noted by SBTi), emissions savings in the Net-Zero scenario from the sector would be approximately 150 Mt CO_2 greater in 2050.

BOX 5

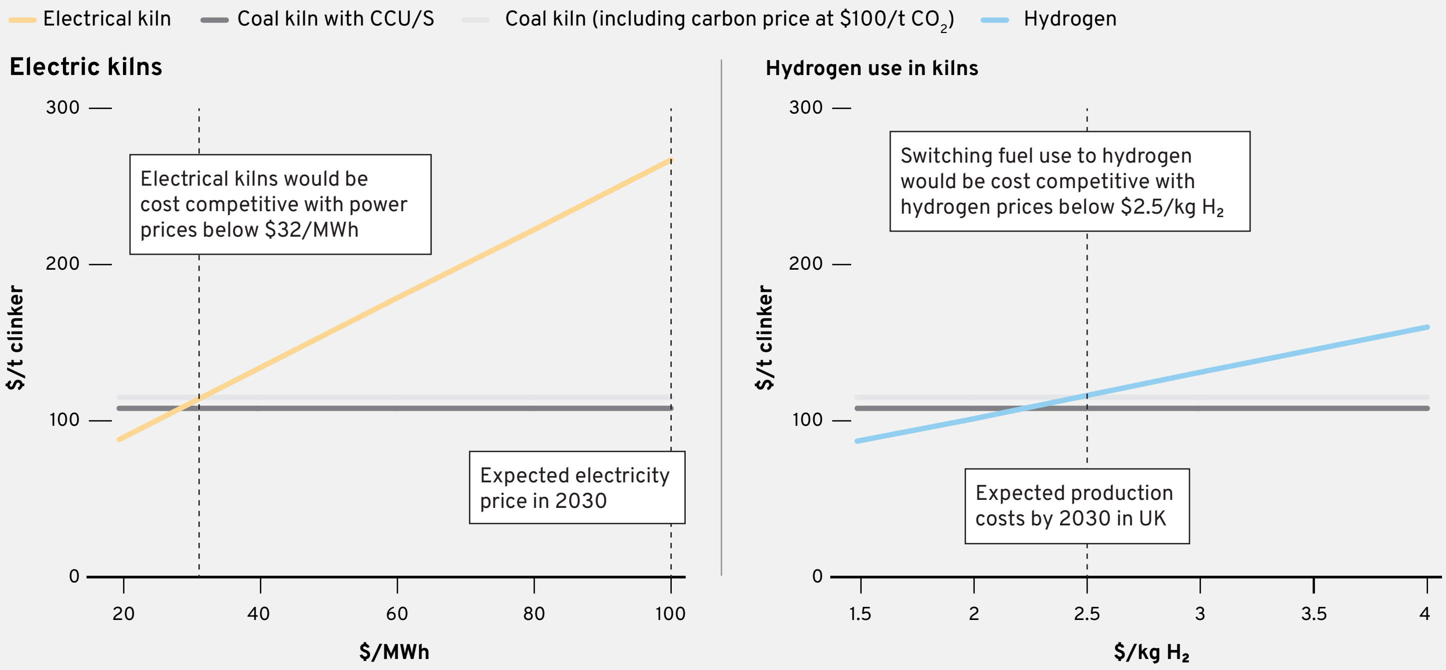
Costs and system impact of electric kilns

The levelised cost of electric kilns and hydrogen use and their cost-competitiveness compared with coal kilns depend heavily on electricity or hydrogen prices (see exhibit below). Electric kilns could be cost-competitive as soon as power prices are below $32/MWh. This price is unlikely to be achieved for grid connections in all regions before 2050 but is expected to be reachable locally for on-site electricity generation in favourable regions (especially in India and North America).

Nonetheless, where on-site renewables are used, it will likely be necessary to purchase some additional grid power to match electricity supply and demand.

Hydrogen kilns could be cost-competitive for hydrogen priced below $2.5/kg. This price is achievable in India and China from 2030 onward.

Break-even analysis for clinker making for electrical and hydrogen kilns



Electrical kilns would be cost competitive with power prices below $32/MWh

Expected electricity price in 2030

Switching fuel use to hydrogen would be cost competitive with hydrogen prices below $2.5/kg H_2

Expected production costs by 2030 in UK

Source: MPP analysis, hydrogen and power pricing from MPP power and hydrogen modelling

B. Capturing remaining process and heat emissions

CCU/S can address process and heat emissions in cement kilns and is expected to play an essential role in the decarbonisation of the sector. Commercial-scale CCU/S plants are already starting to be deployed, at 90% capture rates. The main advantage of CCU/S is that it offers a decarbonisation option for both energy and process emissions.

The CCU/S process involves capturing carbon from the clinker-making process (process and/or energy emissions), using or storing the carbon, as well as transporting the carbon to the usage or storage location. Each part of the process has its own cost, TRL, and barriers to uptake.

CO_2 capture

Multiple technologies exist or are being developed to capture CO_2. Each has different energy consumption, costs, and TRLs (Box 6).

Capture rates and energy needs with current technologies pose significant challenges for carbon capture:

- To be 1.5°C aligned, carbon capture processes in cement have to deliver at least 95% **capture rates**, increasing from the 90% capture rate achieved with today's processes.[57] If the 95% capture rate target is not achieved, residual Scope 1 emissions (of the order of 80–100 Mt CO_2 in 2050) will need to be offset. As this is beyond the savings offered by recarbonation, further savings from other levers or carbon dioxide removal technologies would be required (representing 2%–3% of the total global forecast CDRs in 2050).[xxvi]

- Without further development, carbon capture represents a significant **energy demand** (e.g., 1.5 to 7 megajoules/kg CO_2 for post-combustion).[58,xxvii] This energy demand could lead to a 60% increase in energy used in the total concrete- and cement-making process. This energy could be delivered through the grid where zero-carbon electricity is available, through on-site renewable electricity and local waste heat, or through off-site low-carbon heat.

New capture technologies could reduce up-front investments, decrease energy demand, and increase capture rates to 95%. For example, indirect calcination could lower the investments by a factor of 50%–75% and decrease energy consumption by a factor of 85% compared with post-combustion capture. An overview of carbon capture technologies is given in Box 6. Most of these technologies are in development (with TRLs ranging from 6 to 8) and are expected to be deployed in the late 2020s.

> ***Under the right conditions and if well regulated, CO_2 can be safely stored in geological formations with minimal risks of significant accidental CO_2 release.***

CO_2 utilisation

CO_2 captured from a cement plant can be utilised in other processes. This is consistent with a 1.5°C target if it is stored in a near-permanent form. The viability of usage therefore depends on whether the usage is long term or short term.

- **Long-term utilisation** (i.e., 50-plus years) is equivalent to storage and, depending on the source, can result in either a net removal or reduction in emissions. Long-term utilisation options have significant crossover with the production of cement, carbon curing, and use in aggregates. This crossover presents decarbonisation opportunities, particularly for cement sites that lack straightforward and low-cost access to geological storage. (Box 7 illustrates the example of long-term sequestration in concrete).

- **Short-term utilisation** (i.e., less than 50 years) does not achieve permanent sequestration, since the CO_2 is released into the atmosphere after a relatively short period. If the CO_2 released is originally derived from a biomass or direct air capture source, short-term use enables net-zero emissions. If the CO_2 is derived from a point source, short-term use improves 'carbon efficiency' by using the same molecule twice but does not deliver a net-zero emissions result.

CO_2 storage

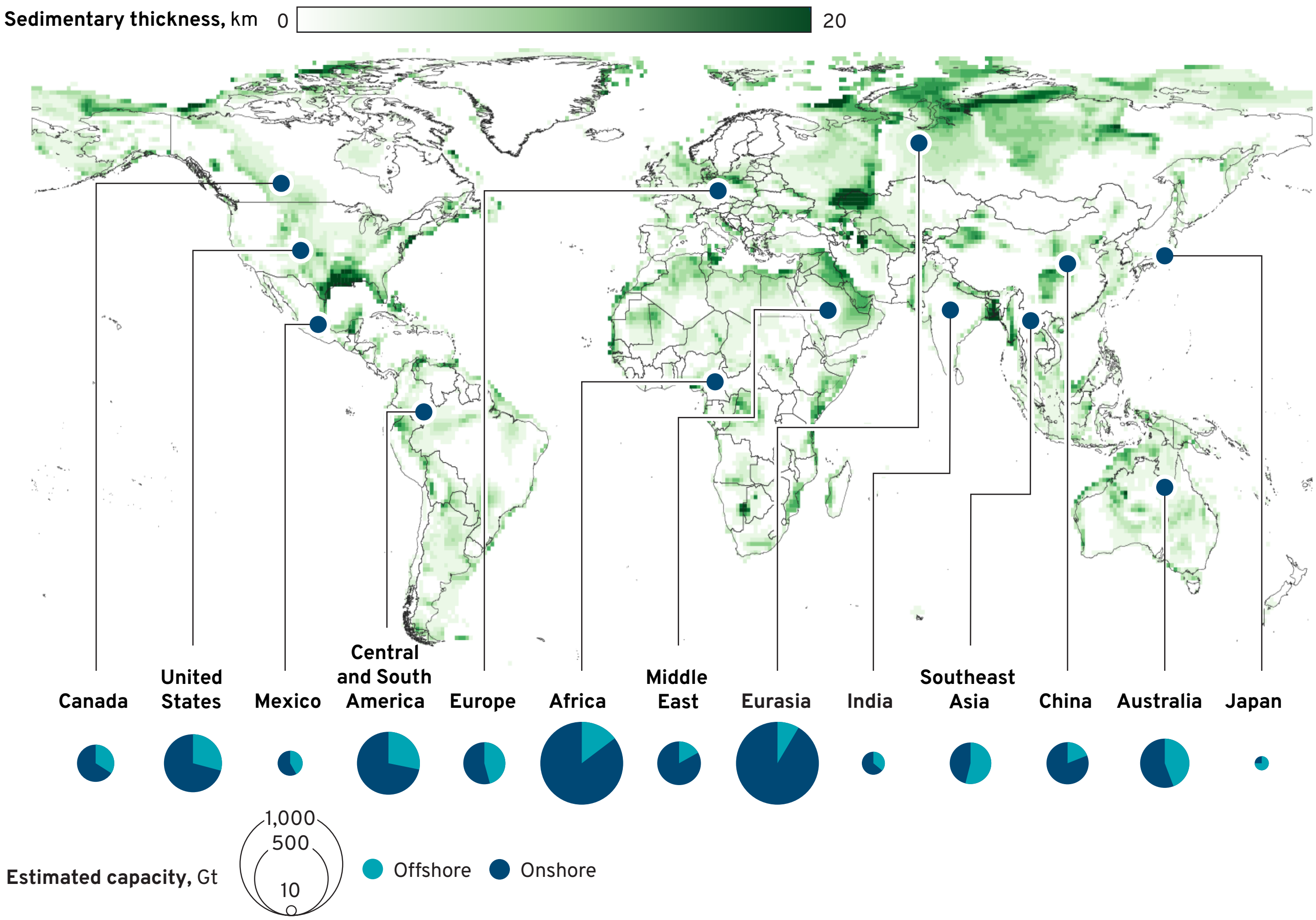
Under the right conditions and if well regulated, CO_2 can be safely stored in geological formations with minimal risks of significant accidental CO_2 release. Geological assessments (Exhibit 1.16) indicate that total storage capacity is largely sufficient globally to absorb the quantities of CO_2 capture envisioned in the Net-Zero scenario, but unevenly distributed across regions and countries. In MPP's Net-Zero scenario, the captured carbon from the cement sector would represent 11%–23% of all global forecast CCU/S deployment across sectors.[59] Storage costs, at around \$10–\$20 per tonne (t), are usually significantly lower than capture cost. The key challenge is therefore not the cost of storage, but the access to storage from cement production facilities.

[xxvi] Based on 3 to 5 Gt of CO_2 removals from bio-energy carbon capture or direct air capture (ETC, *Carbon Capture, Utilisation and Storage in the Energy Transition: Vital but Limited*, 2022).

[xxvii] Specific primary energy consumption unit of CO_2 avoided.

Geographic locations of potential CO_2 storage

Theoretical CO_2 storage capacity, $GtCO_2$



Note: Map shows onshore basins and practically accessible offshore basins. Regions with high volumes of sedimentary basin are correlated with higher CO_2 storage capacities. Offshore capacity estimates exclude sites in water depths of more than 300 metres or that are more than 300 kilometres offshore. The Arctic and Antarctic regions are also excluded.

Source: ETC[60]

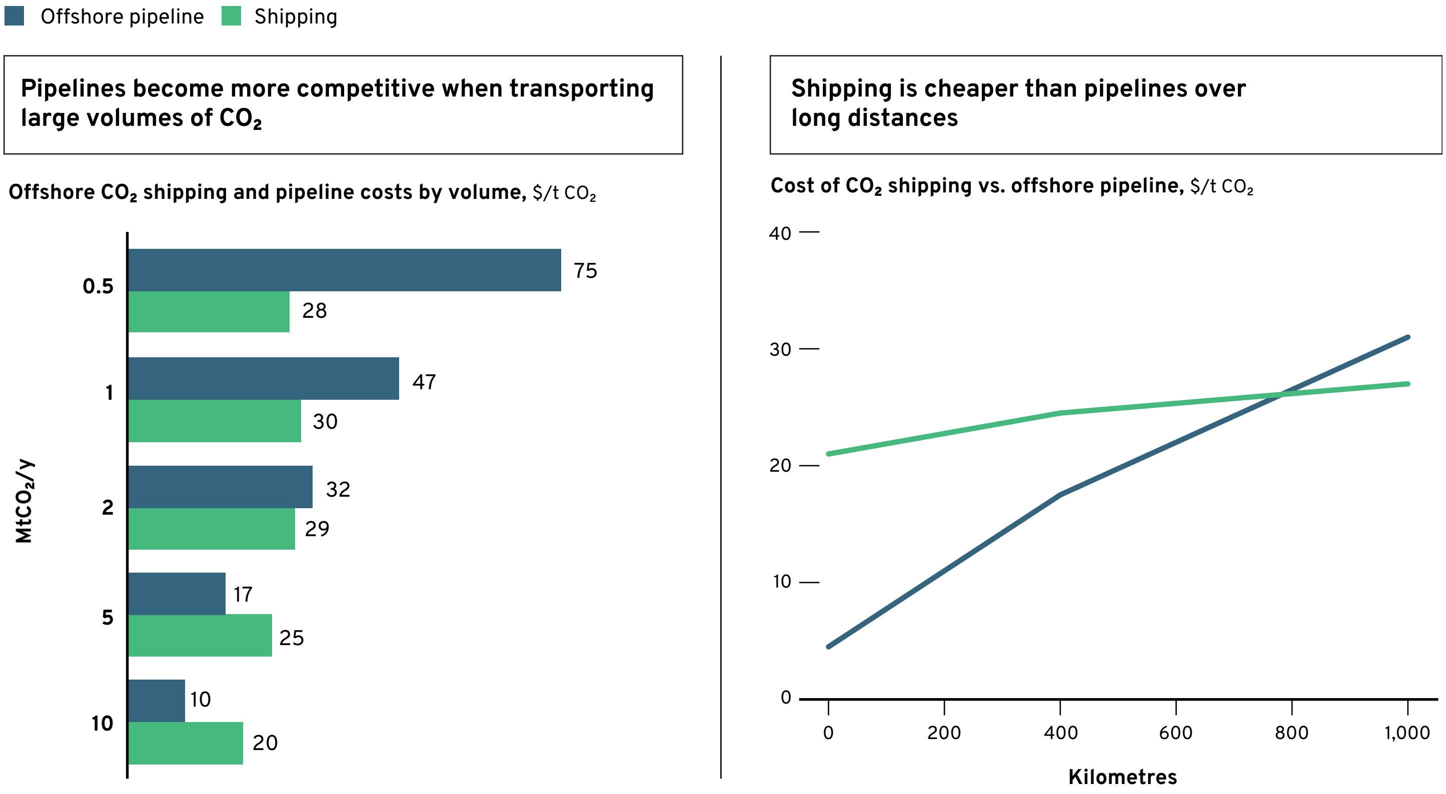
CO_2 transport

Unless CO_2 is captured at or immediately next to a storage or utilisation site, some form of transportation will be required. There are three principal options for transporting CO_2: pipelines, ships, and trucks. Rail is also sometimes considered, but not widely used today. The cost of transportation depends on the transportation mode, as well as a mix of geographic and scale factors. The CO_2 volume transported and distance to CO_2 storage locations are examples of two critical determinants in this context (Exhibit 1.17).

Delivering transport, storage, or usage infrastructure to current cement sites presents a significant scale and funding challenge. Concrete and cement production facilities are geographically dispersed, making it necessary for almost all countries to have CCU/S transport infrastructure available. To capture 1.2 to 1.6 Gt of CO_2 by 2050, almost 90% of the kilns would need to be equipped with carbon capture units.

EXHIBIT 1.17

CO_2 transport costs through pipelines and shipping



Source: ETC, Carbon Capture, Utilisation and Storage in the Energy Transition: Vital but Limited, 2022

To minimise transport, cement plants would benefit from being located within a CCU/S cross-sectoral hub or cluster network, which brings together multiple CO_2 emitters and off-takers and at least one storage operator through shared transportation infrastructure. Regions offering both a high concentration of emitting industries and nearby capacity to store captured emissions are considered prime sites for hub-and-cluster developments.

However, the distribution of cement plants does not always match with the optimal location of hubs. Decisions for cement plants have usually been made based on proximity to raw materials (limestone) and the end market. Therefore, cement kilns are located all over the world and not necessarily next to ports, CO_2 storage sites, or other industry that might use carbon capture. To fully understand this challenge, further analysis should map in detail the combination of cement sites, other existing or future industries capturing or using carbon, and CO_2 storage sites. For cement sites that are neither in an industrial cluster nor near a CO_2 transport and storage project, local deployment of industrial-scale carbon dioxide mineralisation, curing concrete, or usage in aggregates or other products could also be an option (Box 6).

In conclusion, CO_2 capture, utilisation, storage, and transport technologies are both available and critical to decarbonise the concrete and cement sector. Due to its current TRL, CCU/S is expected to deploy from 2030 onward, following an S-curve toward 2050. Nevertheless, the costs of applying carbon capture to cement plants are significant, as they almost double clinker-making costs. Furthermore, the cost-competitiveness of carbon capture is highly dependent on a carbon price that, if above the capture cost, would naturally help bridge the cost premium.

The decision on what to do with the captured CO_2 depends on local conditions. In industrial clusters where transport and storage projects have multiple users (such as chemicals and removal options), cement plants can make use of shared CO_2 storage and transport infrastructure, achieving economies of scale. For cement plants in geographically isolated areas or far from geological storage sites, carbon capture can be combined with on-site or close usage/storage options such as use in aggregates or carbon curing. When CO_2 is captured and used for another purpose such as e-fuels production, careful consideration will have to be given to the carbon footprint. In order for the concrete and cement sector to be on a 1.5°C pathway, carbon use has to offer a form of permanent storage, for example through aggregates or plastics, depending on their recycling potential.[xxviii]

Because concrete and cement are used across a broad geographic footprint, almost all countries will require CCU/S

[xxviii] A full description of the challenges and considerations of usage can be found in ETC, *Carbon Capture, Utilisation and Storage in the Energy Transition: Vital but Limited*, 2022.

infrastructure as well as policies to incentivise and manage this growing infrastructure, including regions where storage potential is challenging. Governments could therefore start designing and implementing related policies to ensure successful adoption in the next decade. This includes providing tax credits or subsidies for CCU/S projects (such as the 45Q tax credit in the United States), creating a robust legal and regulatory framework for carbon accounting of CO_2 storage, and offering blended finance with the private sector for CCU/S projects. The wider role of carbon capture and associated transport, storage, and utilisation is explored in detail in the ETC report *Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but Limited.*[61]

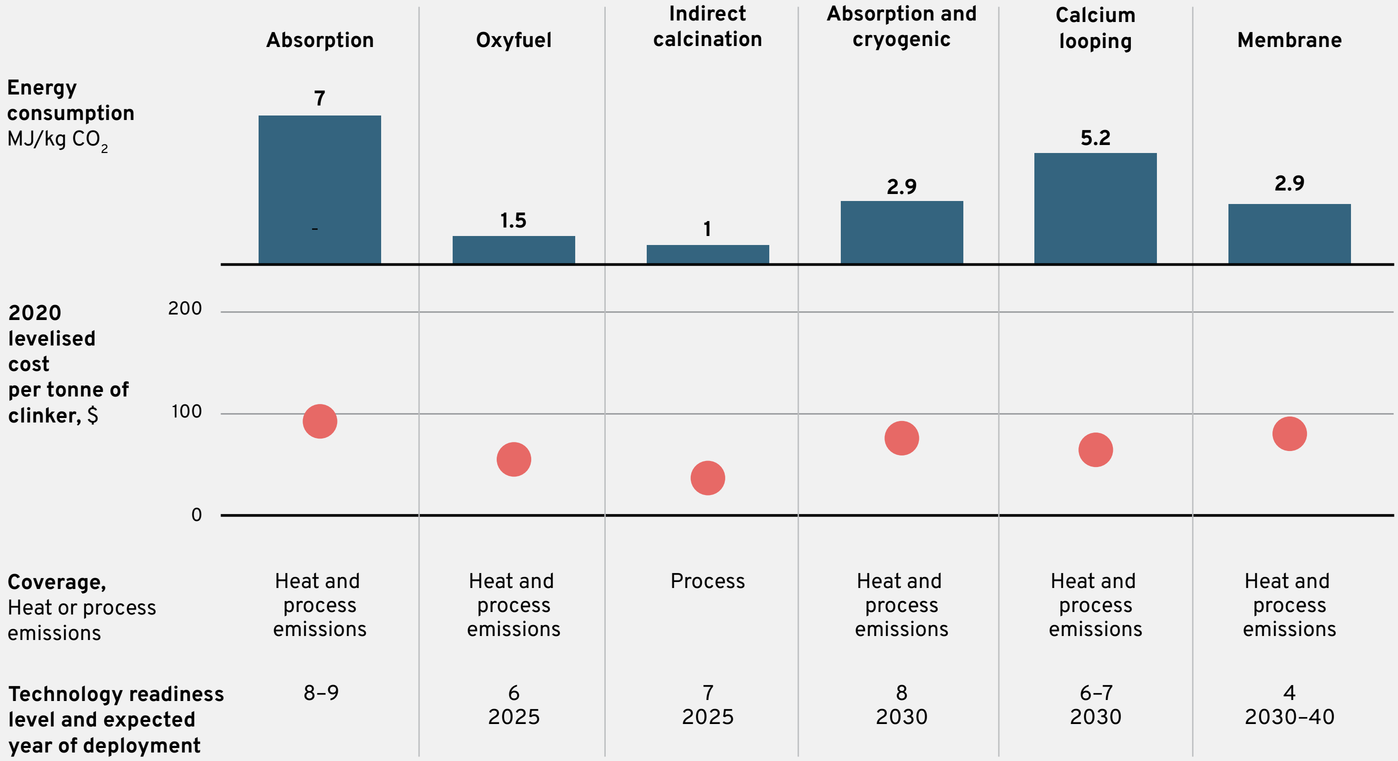
BOX 6

CO_2 capture technologies

Although absorption-based capture is the leading technology available today, a variety of CO_2 capture technologies exist (they are listed below and compared in the exhibit). If new technologies attain commercial deployment, they could reduce carbon capture costs through increased energy efficiency, reduced capital expenditures, and improved CO_2 capture efficiency and purity.

- **Absorption** is a common capture process based on the reaction between CO_2 and a (chemical) solvent.
- **Oxyfuel combustion** is a technology where the fuel is burned in oxygen rather than in air, which generates a purer CO_2 concentration.
- **Adsorption and cryogenic** is a process in which a material attracts CO_2 molecules to its surface.
- **Calcium looping** removes CO_2 from the gases using a calcium oxide (CaO) sorbent.
- **Membranes** can separate gases based on the permeability difference between different gasses.
- **Indirect calcination** indirectly heats the calciner, which keep the heat emissions and process emissions separated.

Comparison of carbon capture options for the cement sector



Note: The energy consumption is in specific energy consumption for CO_2 avoided.

Source: ECRA experts, ECRA[62]

BOX 7

Long-term sequestration in concrete through carbon mineralisation[xxix]

What is carbon mineralisation and how can it ‘use’ captured CO_2?

Carbon mineralisation (TRL 4 to 8) is the process by which carbon dioxide is permanently converted into a solid, carbonate material. Carbon mineralisation can be carried out either in situ or ex situ.

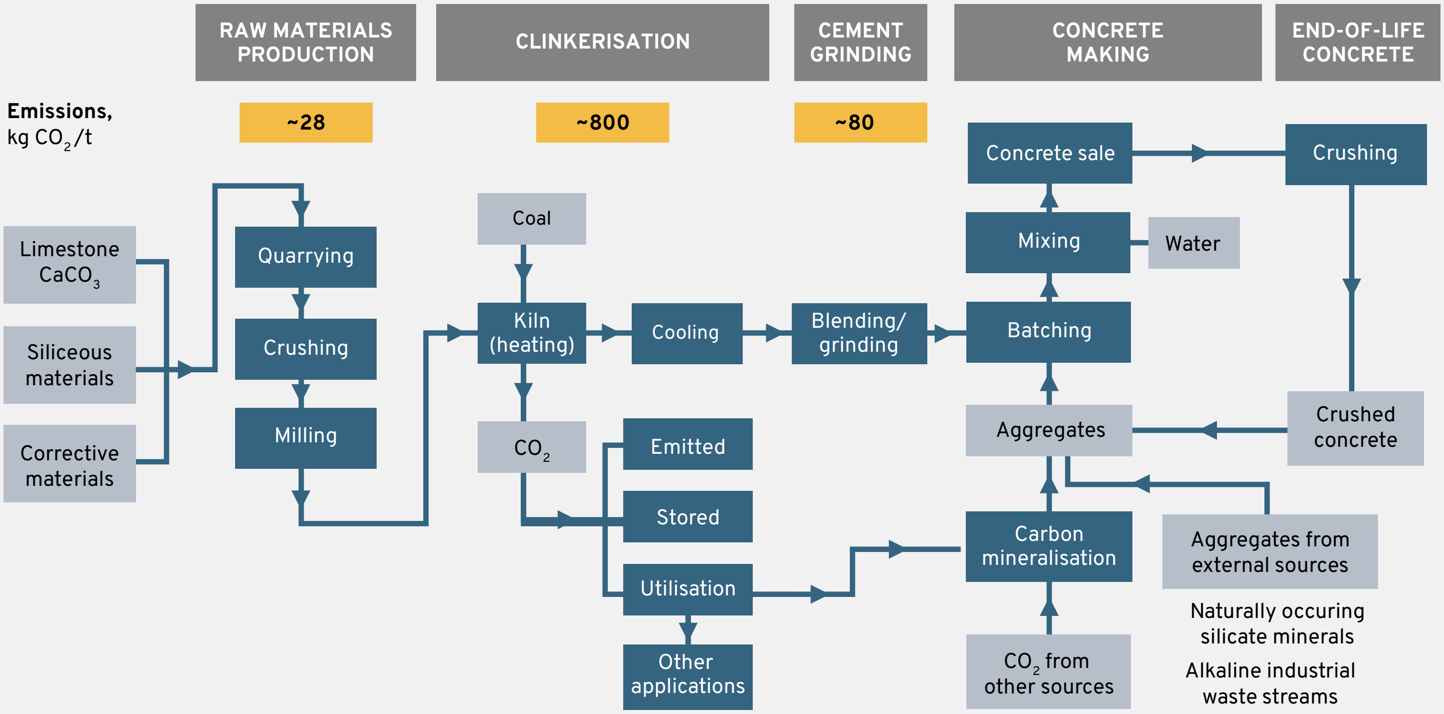
- **In situ** refers to processes that involve injecting a CO_2 solution underground where it reacts with alkaline rocks and solidifies.
- **Ex situ** refers to the aboveground conversion of alkaline minerals (usually calcium- or magnesium-bearing silicates) as they are reacted with CO_2 to form magnesium or calcium carbonates.

In the context of CCU/S, the resultant minerals can be used in various applications, including as aggregates in the production of concrete.

How can carbon mineralisation be used in concrete production?

Concrete is produced from cement, water, and aggregates, typically in an approximate ratio of 1:2:6. Aggregates are inert granular materials such as sand, limestone, gravel, crushed stone, or waste materials such as recycled concrete. They are added to cement and water to create concrete (see exhibit below).

CO_2 generated in the cement production process can be mineralised in aggregates and utilised in concrete production



Source: ETC, Carbon Capture, Utilisation and Storage in the Energy Transition: Vital but Limited, 2022

Carbon mineralisation of aggregates entails coating an existing mineral particle or substrate with a solution of CO_2, water, and alkaline feedstock. This coating process locks in captured CO_2 as a carbon-sequestering layer is formed. The final particle can contain up to 44% CO_2 by mass. Given that global annual demand for crushed stone aggregated in construction is around 50 billion tonnes, significant quantities of CO_2 could be sequestered permanently this way.

The potential of mineralisation in providing a sink for CO_2 captured by the cement industry is highly uncertain but has significant potential and will depend on a mixture of storage availability, waste streams, and the underlying development of the economic case. The ETC currently assesses that approximately 0.4 Gt CO_2 could be utilised in aggregates in 2050 (taking into account limits on injection and deployment). In order to unlock the potential that mineralisation may provide, regulation is required both in terms of ensuring good-quality investable sequestration and in the use of the materials themselves.

[xxix] Reproduced from ETC, *Carbon Capture, Utilisation and Storage in the Energy Transition: Vital but Limited*, 2022

ACHIEVING NET ZERO: POSSIBLE TRAJECTORIES

BOX 8

How are the scenarios modelled?

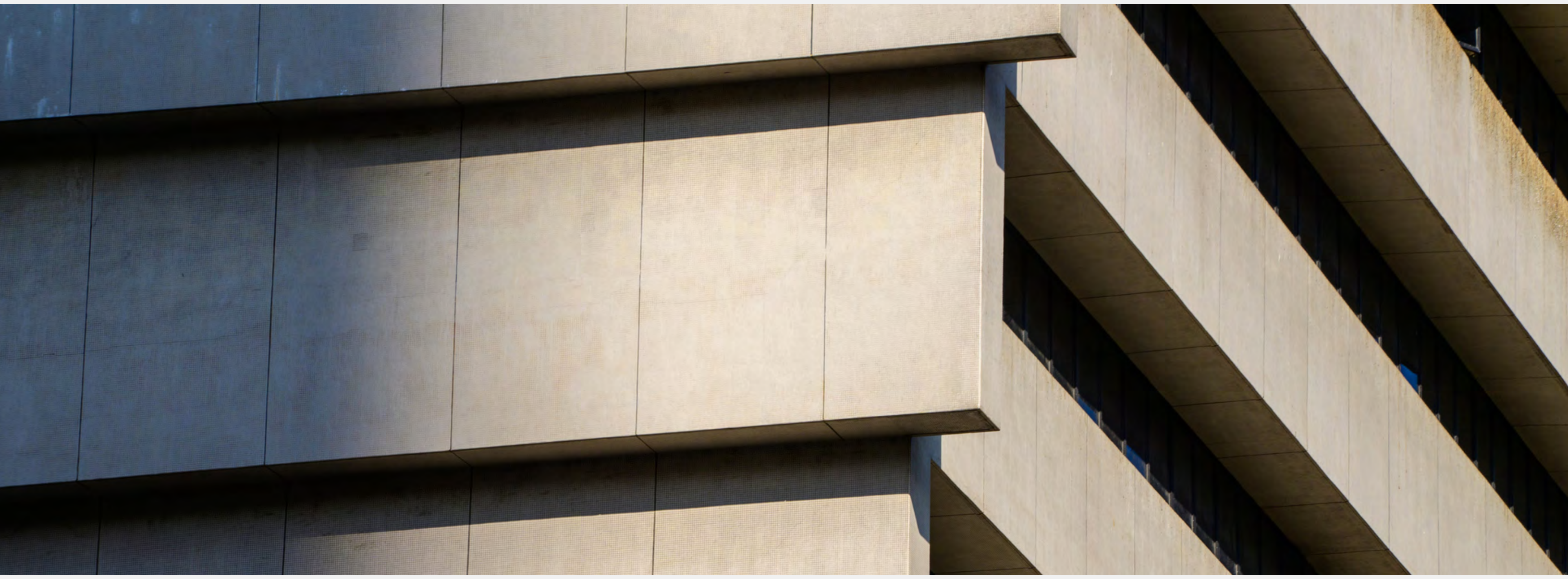
The Concrete and Cement Sector Transition Strategy illustrates various potential 1.5°C pathways in the sector through different scenarios and sensitivities. The scenarios describe cement demand and production in a given year and for a given geography, as well as the related emissions, energy consumption, and required investments.

The scenarios are based on an assessment of what demand reductions and clinker efficiency can be made based on a review of available evidence (summarised in Sections 1.3.1 and 1.3.2). For demand reductions, the central assumption is a 22% market reduction by 2050 compared with a base scenario. For clinker efficiency, the central assumption is that the clinker-binder ratio falls to 0.52 by 2050. These assumptions were then coupled with a bottom-up modelling of decision-making for clinker production, aiming to minimise the total cost of ownership within a given set of constraints.[xxx]

The clinker model focuses on different technology processes under which concrete and cement could be produced. The model rests on two key principles:

1. The uptake of technologies that reduce emissions associated with clinker production is dictated by costs and technology availability.
2. Location-based circumstances such as local energy prices and the availability of carbon storage sites (or utilisation opportunities) determine the optimal cost-effective technology choice.

Further information on the model can be found in the online explorer.



[xxx] Total cost of ownership is calculated based on the total cost of clinker production, both capital and operating costs, over the lifetime of the clinker plant. Key constraints include the potential availability of carbon capture infrastructure.

2.1 Scenario definitions

Different combinations of the portfolio of decarbonisation measures in the concrete and cement sector can deliver a net-zero sector. In particular, the emergence of new technology allows further expansion of the possible pathways.

By modelling the Base scenario, a core trajectory to net zero by 2050, and a set of associated sensitivities, the Sector Transition Strategy aims to illustrate the potential pace of change and trade-offs under different circumstances and highlight the prerequisites in terms of required investments, resource demand, and 2030 milestones to kick off the transition. The scenario definitions are:

- **Net-Zero scenario:** This scenario reflects a world where significant focus and investment occur to enable the net-zero transition in a way consistent with a 1.5°C pathway. The Net-Zero scenario is built from the GCCA 2050 roadmap, combined with analyses from the ECRA technology papers and MPP to determine the current and future supply of clinker. Bringing together these sources provides a deep understanding of the underlying decarbonisation drivers and trade-offs within and outside the sector.

  In the Net-Zero scenario, a carbon price is determined in such a way that it enables a 1.5°C scenario. This set price acts as a proxy for the actions that are needed to close the competitiveness gap between conventional concrete and cement production processes and those required to realise near-zero emissions. Because not all geographies will use a literal carbon price, the carbon price used in these scenarios represents a combination of price, regulatory, and market changes. A variety of policy and value-chain levers can take the place of explicit carbon pricing. Examples of such levers include the creation of differentiated markets for low-CO_2 concrete and cement, targeted capital, operational expenditure subsidies for the deployment of near-zero-emissions technologies, and other regulatory measures that raise the cost of high-emissions technologies.

- **Base scenario:** To gauge real-world impacts, the Net-Zero scenario and sensitivities are compared with a Base scenario reflecting a world where demand for concrete and cement increases, and the industry continues to deliver energy efficiency improvements but does not invest in low-carbon initiatives and technologies.

- **Sensitivity analysis:** In addition to these two core scenarios, MPP defines three other scenarios as part of a sensitivity analysis. These pathways are designed to illustrate some of the key uncertainties faced by the sector:

  - **Rapid Barrier Elimination scenario:** This scenario assumes an earlier and more rapid uptake of concrete and clinker efficiency improvements as well as more rapid uptake of carbon capture technology from 2030 onward. This scenario is consistent with the SBTi emissions trajectory.

  - **Innovation in Heat Decarbonisation scenario:** This scenario assumes that the use of hydrogen and electricity to heat kilns becomes cost-competitive more rapidly. It is assumed such low-carbon heat technology rolls out at scale from 2035 onward and reaches 20% market share by 2050.

  - **Limited Barrier Elimination scenario:** Compared with the Net-Zero scenario, this scenario assumes a delayed time line to eliminate barriers for demand-side levers, clinker substitution solutions, and carbon capture. The scenario assumes that concrete, cement, and clinker efficiency develop less rapidly in the 2020s, and that mass deployment of carbon capture starts in 2040 instead of 2030.

It is important to note that the scenarios presented are not forecasts, but instead illustrate potential trajectories for the concrete and cement industry under different assumptions. The sector can evolve in multiple different ways, particularly regarding new and emerging technologies. These scenarios demonstrate that there is potential should these new and emerging technologies commercialise. More detail on the scenarios is provided in Exhibit 2.1.

EXHIBIT 2.1

Summary of scenarios and their characteristics (based on the three key levers)

				SENSITIVITY ANALYSIS		
		BASE SCENARIO	**NET-ZERO SCENARIO**	“Rapid barrier elimination”	“Innovation in heat decarbonisation”	“Limited barrier elimination”
Net-Zero and 1.5°C aligned		No	Yes	Yes	Yes	No
Carbon tax		None	\$50/t CO_2 in 2025, rising to \$100/t CO_2 in 2050	None	As Net-Zero scenario	\$0/t CO_2 in 2030, rising to \$100/t CO_2 in 2050
Use concrete more efficiently	**Demand reduction in concrete, cement, and clinker**	None	Demand reductions compared with 2050 Base scenario: • Concrete: 22% • Cement: 14% • Clinker: 17%	Demand reductions compared with 2050 Base scenario: • Concrete: 32% • Cement: 22% • Clinker: 27%	As Net-Zero scenario	Demand reductions compared with 2050 Base scenario: • Concrete: 13% • Cement: 8% • Clinker: 12%
Reduce process emissions	**Alternative chemistries**	None	Deployed in limited amounts from 2030	As Net-Zero scenario	As Net-Zero scenario	As Net-Zero scenario
Bring remaining emissions close to zero	**CCS rollout constraint**	None	Mass deployment from 2030 following S curve to 2050	Mass deployment from late 2020s following S curve to 2040	As Net-Zero scenario	Slow-moving deployment without any accelerations from now to 2050
	Emerging technologies	None	Hydrogen deployed in limited amounts from 2030	As Net-Zero scenario	From 2035, electrification and hydrogen in kilns deploys rapidly to 20% market share by 2050	As Net-Zero scenario

Note: The modelling assumes that carbon transport and storage is available in line with the CCU/S rollout constraint. This is a critical assumption in determining the rollout profile of CCU/S.

Source: MPP analysis

2.2 What it will take to achieve a net-zero concrete and cement sector

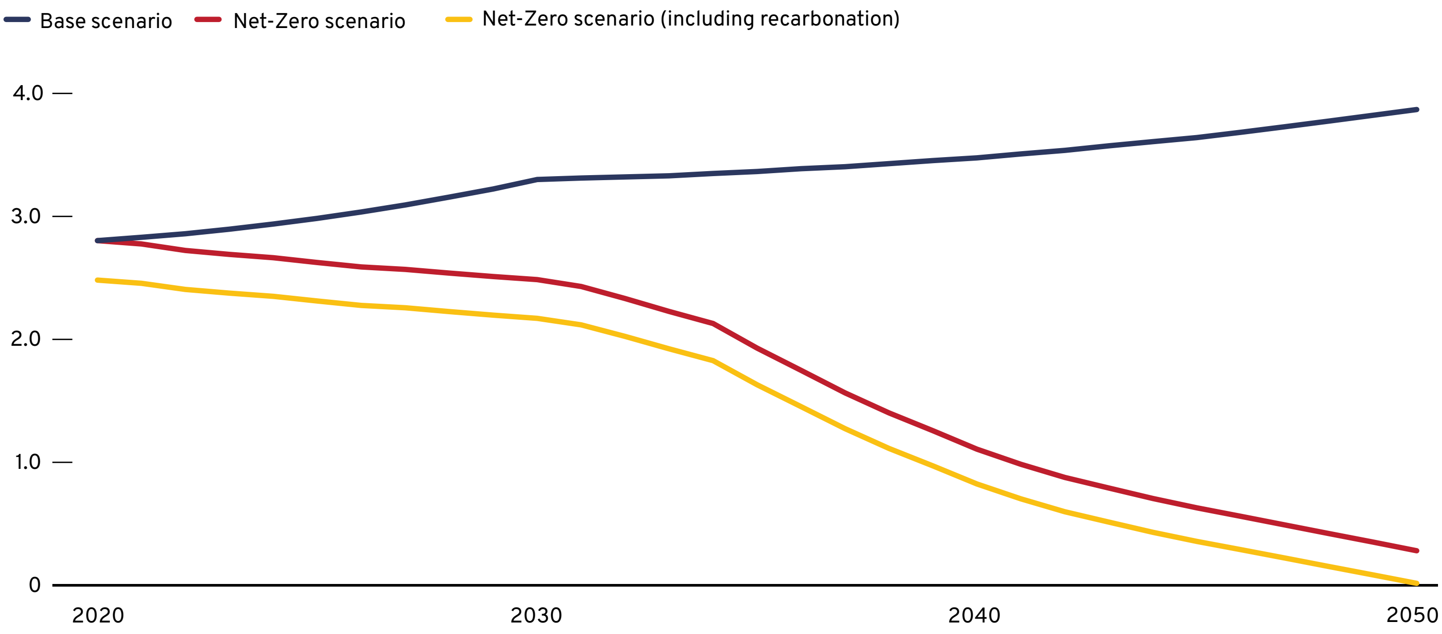
2.2.1 Halving emissions by the mid-2030s

Under the Net-Zero scenario, the sector reduces Scope 1 and 2 emissions by 13% to 30% by 2030, by 50% by the mid-2030s, and by 91% by 2050 (Exhibit 2.2). The remaining 9% of emissions can be addressed through negative emissions, such as natural recarbonation. This scenario has implications for the evolution of concrete and cement technologies, emissions, energy requirements, and financing needs, which are explored in detail in the rest of this section.

EXHIBIT 2.2

CO_2 emissions trajectory

Annual CO_2 emissions, Gt CO_2



Note: Includes Scope 1 and 2 emissions. Recarbonation refers to the process where lime (CaO) in cement reacts with carbon dioxide (CO_2) in the air and forms calcium carbonate ($CaCO_3$) throughout concrete's lifetime. This means the cement absorbs CO_2 from the air, offsetting some of the carbon emissions of production. The level of recarbonation will depend on the composition of the cement produced.

Source: MPP analysis

2.2.2 Compatibility with a 1.5°C carbon budget

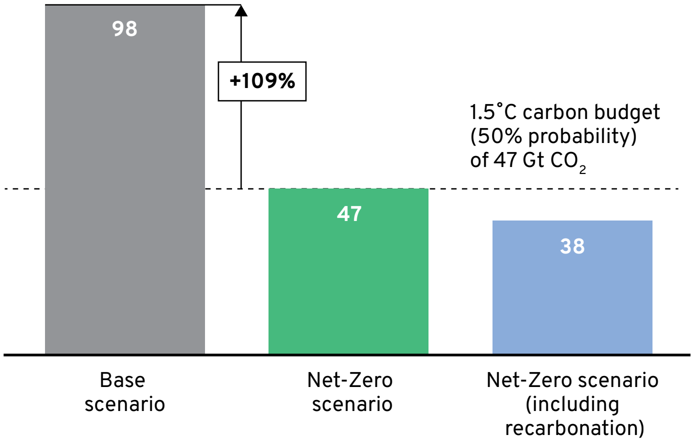
With no decarbonisation action (the Base scenario), the concrete and cement sector would overshoot the 1.5°C carbon budget by 109% in 2050 (Exhibit 2.3). In contrast, the Net-Zero scenario stays within the 1.5°C carbon budget of 47 Gt CO_2 by 2050.[xxxi] When accounting for recarbonation, cumulative emissions between 2022 and 2050 are estimated at 38 Gt.

Although the Net-Zero scenario is consistent with the 1.5°C carbon budget, early action is important because climate change is driven by cumulative emissions in the atmosphere. Achieving efficiency gains in clinker, cement, and concrete use early and implementing carbon capture and other breakthrough technologies earlier could increase costs in the short term and play a significant role in limiting the probability of the sector overshooting its carbon budget.

EXHIBIT 2.3

Comparison of 1.5°C carbon budget with cumulative emissions of modelled scenarios

Cumulative CO_2 emissions between 2022 and 2050, Gt CO_2



Source: MPP analysis

[xxxi] The calculation of the carbon budget for the cement sector typically does not include the impact of recarbonation. These numbers are therefore presented separately. The amount of carbon captured through recarbonation is dependent on the volume of concrete used over the period.

2.2.3 Evolution of concrete and cement sector emissions

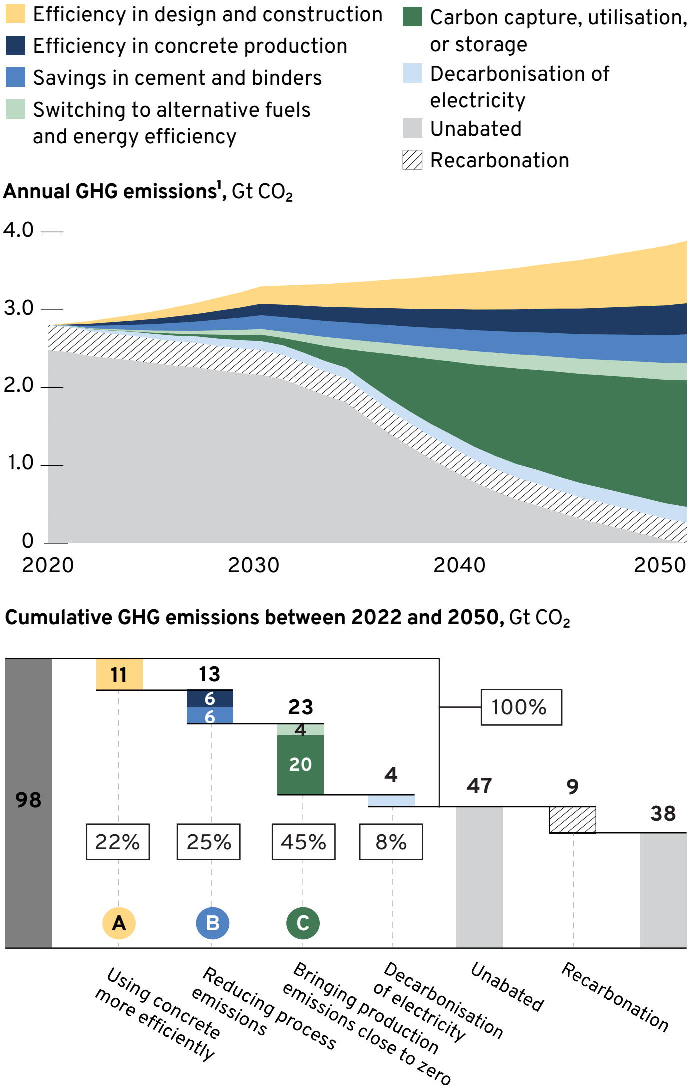
There is not one 'silver bullet' technology that can fully decarbonise the concrete and cement sector. All three levers highlighted in Section 1.3 – namely, using concrete more efficiently, using less clinker in concrete, and eliminating and capturing emissions in the clinker-making process – are necessary. In the Net-Zero scenario, between 2022 and 2050, efficient use of concrete could lead to a cumulative emissions savings of 22%; using less clinker could lead to a cumulative emissions savings of 25%; and the elimination and capture of carbon could lead to a cumulative emissions savings of 45% (Exhibit 2.4). Increased action in this decade is critical, with demand reduction and increased use of SCMs as first steps, complemented by first-of-a-kind deployment of CCU/S and R&D for new technologies to enable a broader range of decarbonisation options in the 2030s and beyond.

Maximizing the demand reduction levers does not mean that limited efforts need to be made within the cement sector in the near term. The Net-Zero scenario illustrates a specific portfolio of decarbonisation action that could deliver a net-zero sector by 2050 (though other combinations could also deliver a net-zero sector). Given the low cost and technological readiness, SCM use is increased in the 2020s, using newly available SCMs including calcined clay. From 2030, carbon capture deploys rapidly across all sites due to an increasing carbon price making the business case viable. This roll out of carbon capture depends on local availability of transport, storage, and usage solutions. From 2030 onward, the Net-Zero scenario also assumes a small but growing role for alternative chemistries and hydrogen (though some may be deployed in limited levels before 2030). This assumption is based on GCCA's assessment and is illustrative, as the role of alternative chemistries and hydrogen could significantly differ (as highlighted in Section 2.2.4).

New breakthrough technologies such as alternative chemistries are not deployed at a large scale in the Net-Zero scenario. However, faster deployment could be achievable if they demonstrate scalability, consistent net-zero life-cycle emissions, access to raw materials, and lower-cost production (e.g., compared with carbon capture methods for decarbonisation). Such scenarios are further analysed in the sensitivity analysis.

EXHIBIT 2.4

Annual and cumulative emissions of the Net-Zero scenario

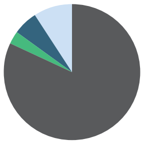
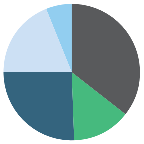


Note: Annual GHG emissions include includes Scope 1 and 2 emissions. Scope 3 upstream emissions would add approximately 3.8 Gt CO_2e of cumulative emissions from 2022 to 2050. Decarbonisation of electricity involves electricity demand for kilns, grinders, and carbon capture.

Source: MPP analysis, GCCA,[63] ECRA[64]

EXHIBIT 2.5

The mix of actions across all lever groups required for the Net-Zero scenario

LEVERS		NET-ZERO SCENARIO 2020	 2050
Using concrete more efficiently Ⓐ	*Compared with base case*		Demand reductions compared with Base scenario in 2050: • Concrete: 22% • Cement: 14% • Clinker: 17%
Reduce process emissions Ⓑ	*Using SCMs (clinker-binder ratio)*	Clinker factor: 0.63	Clinker factor: 0.52
	Alternative chemistries (% market penetration)		5%
Bring remaining emissions close to zero Ⓒ	*Decarbonizing clinker heat*	Coal: 82% Biomass: 3% Waste: 6% Gas: 9% Hydrogen: 0% 	Coal: 36% Biomass: 14% Waste: 26% Gas: 19% Hydrogen: 6% 
	Carbon capture		Capturing 1.6 Gt CO_2
Decarbonisation of electricity	*Electricity demand (TWh)*	Clinker production without CCU/S **210** Grinding and concrete production **250**	Clinker production with CCU/S **525** Grinding and concrete production with efficiency levers **210**
	Electricity emissions intensity (g/kWh)	550	10

Source: MPP analysis

2.2.4 Different routes are possible in the delivery of a 1.5°C pathway

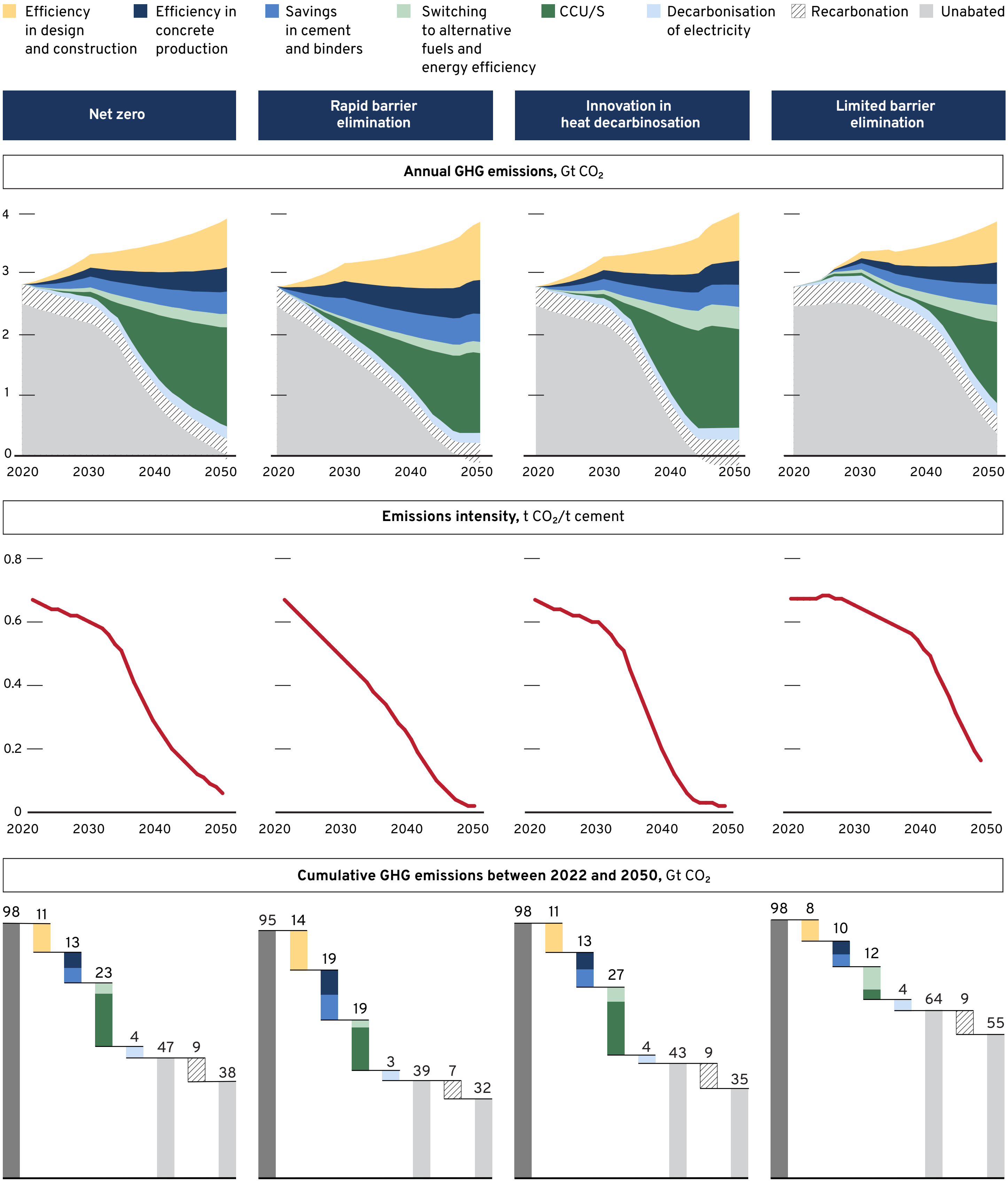
The Net-Zero scenario highlighted in the previous section represents only one of the many potential pathways to a net-zero and 1.5°C-aligned sector. The mix of measures is particularly sensitive to two factors:

1. **Deployment speed:** How fast efficiency measures are delivered depends on how fast policymakers, industry, and users can change behaviour, design, and buying practices, and how industry responds to those changes in behaviour with altered products.
2. **Innovation:** The number and development pace of innovative technologies can vary significantly. The commercialisation time frames for new carbon capture technologies, alternative chemistries, and new heat decarbonisation technologies are key in determining the extent of their rollout by 2050.

Three different trajectories highlighted in Exhibit 2.6 illustrate how these factors could impact the technology mix, focusing on Rapid Barrier Elimination, Innovation in Heat Decarbonisation, and Limited Barrier Elimination.

EXHIBIT 2.6

Decarbonisation curves for the Net-Zero scenario and sensitivity analysis



Source: MPP analysis

The sensitivity analysis highlights three key points:

1. **Immediate action is needed to deliver on a 1.5°C-consistent pathway as well as a net-zero sector by 2050**

   The Limited Barrier Elimination scenario shows that delayed action would result in a 36% overshoot of the 1.5°C carbon budget in 2050. Progress in the 2020s across each of the lever groups is essential as the speed of transformation is limited; the sector can only transform existing capital assets or build new assets within certain time frames. Additionally, transformations to the rest of the value chain and buying behaviour take time to implement.

   The whole value chain has an opportunity to cooperate and manage the transition to a low-carbon future. The risk of delay is that the transition is highly disordered, with the sector having to react to policymaker, buyer, and investor demands, rather than shaping a clear path to net zero. This starts with the sector promoting concrete use efficiency, clinker efficiency, building the supply chain for carbon capture, and investing in R&D for new technologies.

2. **Carbon capture plays a large role in all scenarios**

   Across all scenarios, carbon capture plays a key role in decarbonising the sector, accounting for 35%–50% of cumulative emissions savings. Even where efficiency and SCM deployment is maximised (up to 60% of cumulative emissions savings), carbon capture plays a significant role in decarbonising the sector (approximately 34%), particularly for the remaining process- and energy-related emissions from clinker production. Even where heat decarbonisation technologies become available in the 2030s, they only replace some of the need for carbon capture. To deliver a 1.5°C-aligned scenario, decarbonisation needs to progress as rapidly as possible, making carbon capture essential.

   Carbon capture deployment is ultimately limited because the other options for decarbonisation are more cost-effective and there could be challenges in storing or using the carbon captured in particular locations.

3. **Although uncertain, breakthrough technologies could play a promising role in decreasing the costs of the transition to low-carbon concrete and cement**

   The Rapid Barrier Elimination scenario highlights that even with efficiency improvements and increased SCM deployment, a large share of emissions will still have to be abated within the cement sector. If this is achievable, total costs could be reduced by approximately 17% compared with the Net-Zero scenario because efficiency improvements are more cost-effective than CCU/S.

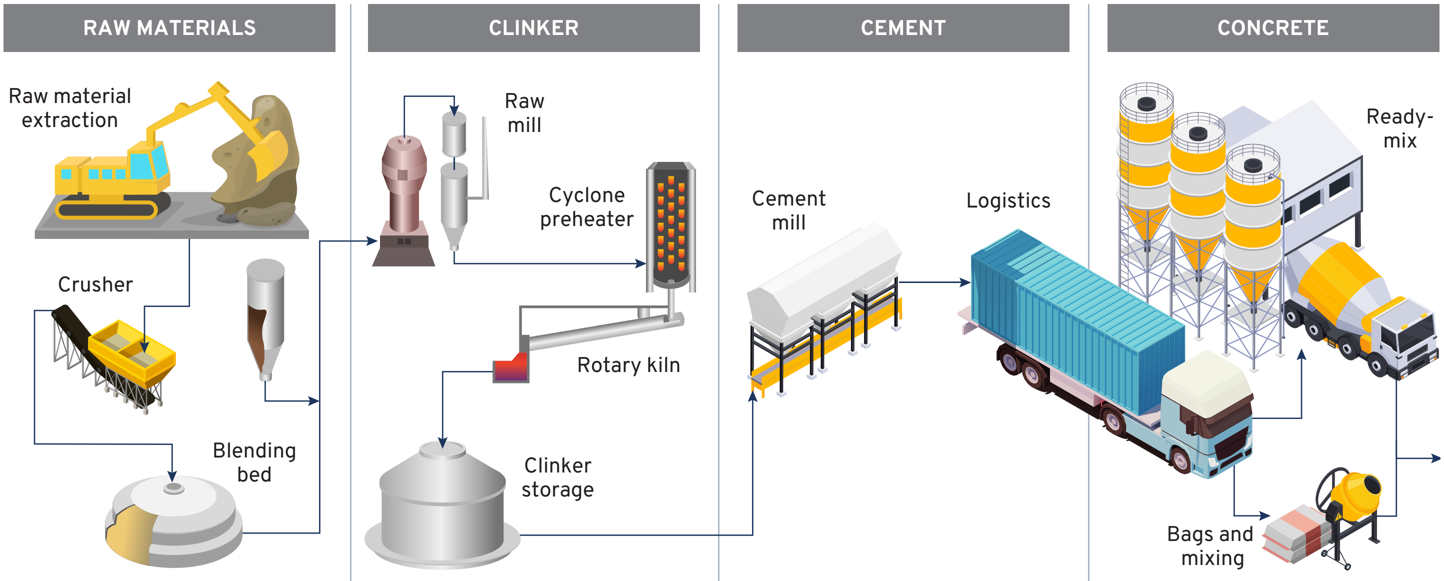
   The Innovation in Heat Decarbonisation scenario also highlights that a mix of technological levers are vital to deliver a 1.5°C-aligned sector. In more detail, the scenario showcases the impact of alternative fuels and electrification if these technologies scale rapidly, from TRL 4 today to mass rollout in the mid-2030s. This could deliver cost savings if electricity can be sourced for less than $32/MWh or hydrogen for less and $2.5/kg. In this scenario the sector would reach net zero by 2045 and undershoot the 1.5°C carbon budget.

   Although innovation could reduce the cost of existing technologies (e.g., carbon capture), new technologies could offer alternative technology pathways, which could be immensely valuable in de-risking the sector's path to a net-zero, 1.5°C-aligned way of operating. Exhibit 2.7 gives an overview of the technological innovations highlighted in Section 1.3 with their respective TRLs, illustrating that alternative chemistries are at an early stage of development, with TRLs of 3 to 4 (technology has been validated in the lab). If developed successfully, these technologies could offer a lower-cost pathway than carbon capture.

EXHIBIT 2.7

Low-carbon concrete and cement innovation landscape

Type of lever 🟨 Use concrete more efficiently 🟦 Reduce process emissions 🟩 Bring remaining emissions close to zero



Alternative raw materials

- Calcium silicate
- Magnesium silicate
- Crushed concrete waste
- Mining tailings
- Steel slags

CCS innovation

- Temperature swing absorption
- Cryogenic capture
- Calcium looping
- Membrane
- Oxyfuel
- Indirect calcination

New heat sources

- Electric kilns
- Green hydrogen

Alternative SCMs

- Calcined clay
- Concrete fines
- Reactive silica from mine tailings
- New or synthetic SCMs

Alternative chemistries

- Belite-rich clinkers
- Calcium sulfoaluminate
- Alkali-activated materials
- Bio-based cement

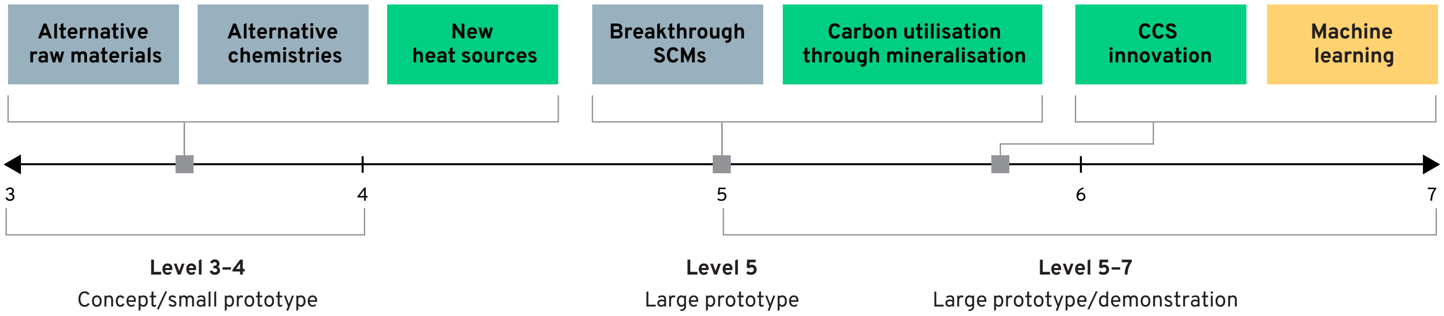
Machine learning

- Optimise concrete mixes

Carbon utilisation through mineralisation

- Injection of CO_2 into ready-mix concrete
- Concrete aggregate with injected CO_2

Technology readiness level



Source: MPP analysis

2.2.5 Energy and raw materials needed to enable the transition

The transition to a low-carbon concrete and cement sector will require a significant shift in the resources needed for its production. The use of coal must decrease significantly while the use of alternative fuels, such as waste, low-carbon electricity, and to some degree hydrogen, must increase. An overview of these demand changes based on the Net-Zero scenario is shown in Exhibit 2.8, which provides the following insights:

- **Low-carbon electricity:** The concrete and cement sector uses electricity for a variety of purposes, including grinding, processing, and, in a decarbonised world, kilns and CCU/S. In the Net-Zero scenario, electricity demand increases by 66% by 2050, of which approximately 50% is used to meet the increased electricity demand for CCU/S technologies.

- **Coal consumption:** By 2050, total coal demand is expected to fall by 50% in the Net-Zero scenario, primarily driven by decreased demand for concrete and cement, as well as switching to alternative (heating) fuels.

- **Alternative fuels:** Alternative fuels grow significantly in the Net-Zero scenario, with biomass demand increasing almost fivefold and waste demand increasing fourfold by 2050. Hydrogen demand is set to increase from 0 today to approximately 6 Mt by 2050.

- **Energy demand from carbon capture:** By 2050, the total energy needed for carbon capture accounts for 35% of total energy demand in the Net-Zero scenario. This energy can be provided through a number of different sources, including on- or off-site low-carbon heat and electricity production, or using the same heat decarbonisation method as used for a kiln. For this analysis, the latter is shown, but this depends on plant setup and could be very different from what is presented in Exhibit 2.8.

EXHIBIT 2.8

Energy and raw materials needed to enable the Net-Zero scenario

■ Clinker production ■ Energy for carbon capture (CCS) ■ Cement production ■ Concrete production

Coal demand, Mt

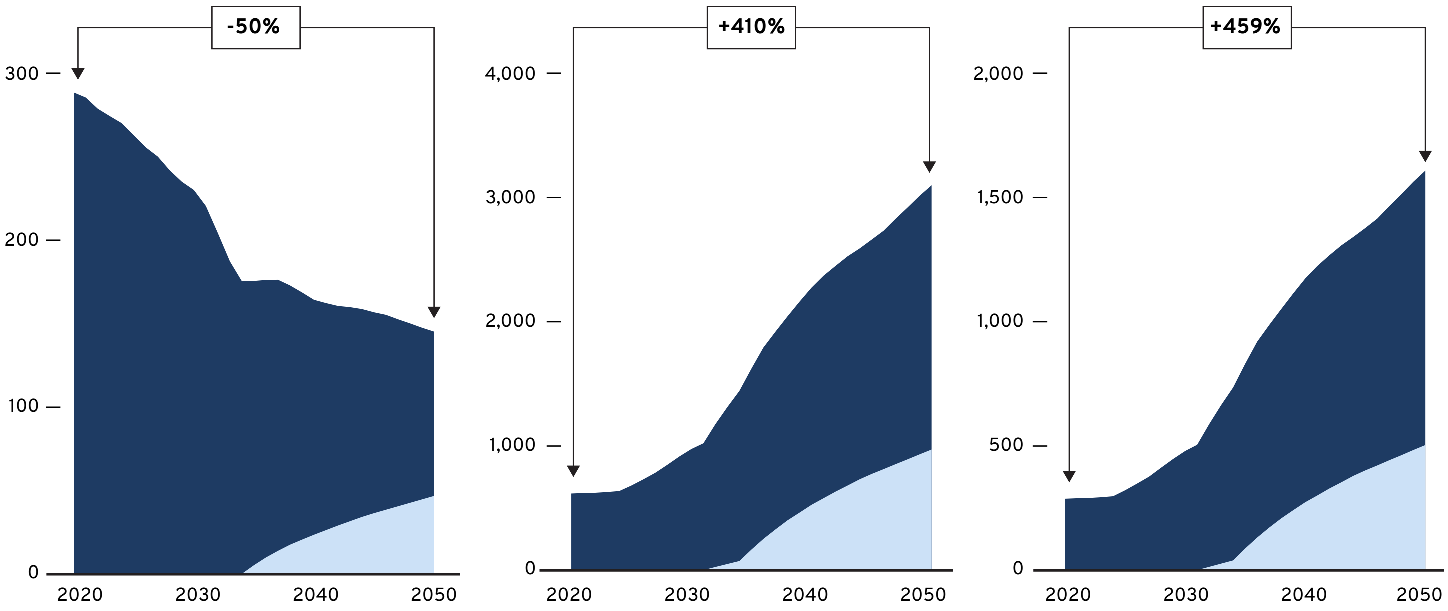
Coal demand falls by over 50%, driven by switches to alternative fuels. This is offset from 2035 by CCS rollout, as CCS increases the coal intensity of production.

Waste demand, PJ

Waste demand faces a similar increase as biomass due to the roll out of alternative fuel–based kilns

Biomass demand, PJ

Biomass demand increased by almost 5 times, representing ~2% of global biomass demand



Hydrogen demand, Mt H_2

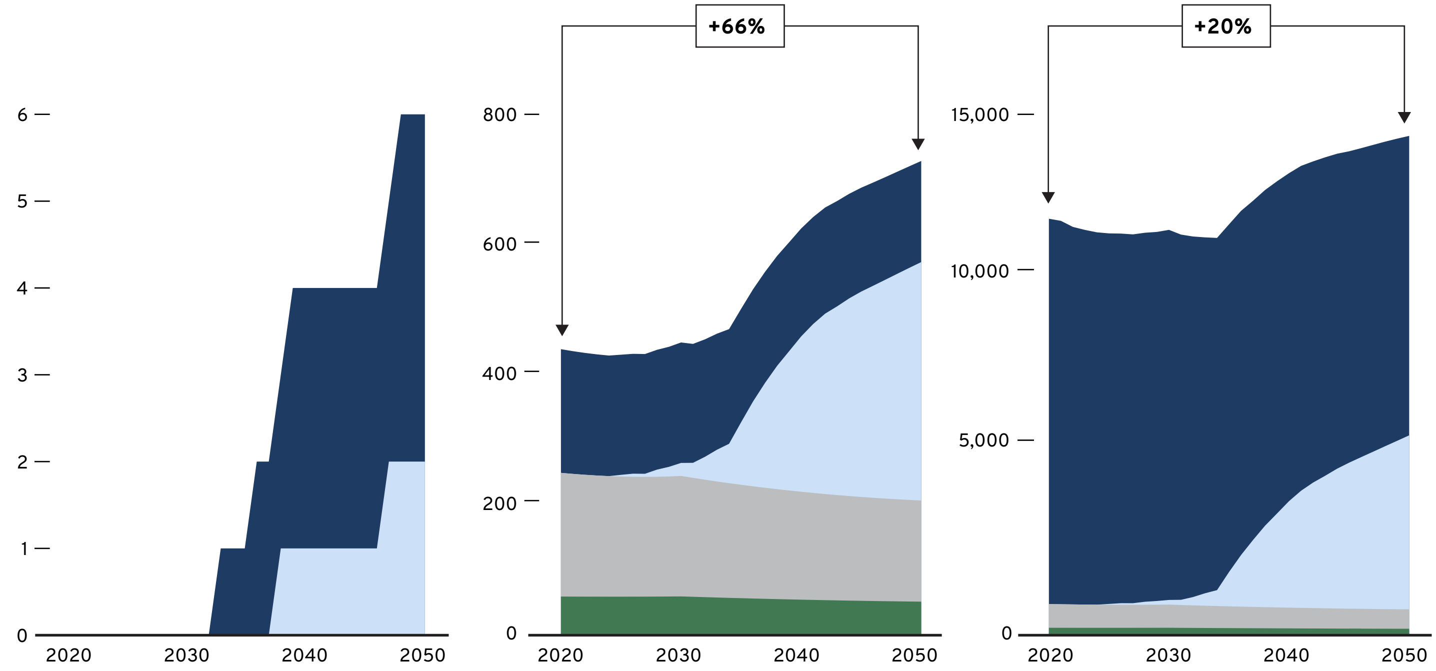
Hydrogen demand rolls out from 2030, and by 2050 represents ~1% of global hydrogen demand

Electricity demand, TWh

Electricity demand increases by 66%, driven by electricity needed for carbon capture

Total energy demand, PJ

Total energy demand increases by 20%, driven by increased energy demands from operating carbon capture



Note: Energy for carbon capture (highlighted in light blue) can be provided in different ways, so should be treated cautiously.

Source: MPP analysis

Note: The previous section focuses solely on the outcomes of the Net-Zero scenario. Alternative decarbonisation pathways can have very different energy requirements, as the energy requirements depend on the combination of decarbonisation levers used. For example, increased SCM use will reduce the energy requirements for heat sources, whereas for every 10% increase in market penetration of electric kilns, electricity demand would increase by 550 TWh.

2.2.6 Investment needed for the transition to low-carbon concrete and cement

Compared with the Base scenario, decarbonising cement and concrete production decreases investment in the sector by 7%, but total investments including the enabling infrastructure increase by 35%.

Decarbonising the sector will require two types of investment (cumulative numbers 2022–50, with a ± 30% margin of uncertainty):

1. **Investment in the concrete and cement sector,** which would decrease from $1,050 to $980 billion, a 7% decrease compared with the Base scenario, which includes no major decarbonisation effort, due to large demand reductions. This decrease would be partially offset by increased investment in carbon capture equipment. Although this is a reduction in absolute numbers, it represents an increase of 24% in investment per cubic metre of concrete.

2. **Investment in enabling infrastructure,** which increases by approximately $300 billion due to the scale-up of low-carbon power and CO_2 transport and storage networks. This investment would be delivered by other enabling sectors and paid for by the concrete and cement sector (in synergy with other user sectors) through operating costs (e.g., electricity prices).

Total investment is expected to increase to approximately $1,400 billion (35% more than in the Base scenario). Because a large share of these investments is related to the high projected use of CCU/S, resorting to CCU/S only where other decarbonisation options are not possible could help decrease the total investment needed.

Reaching net zero requires a transformation in investment distribution, with fewer additional plants than in the Base scenario and an increase in brownfield and infrastructure investments, such as for CCU/S and low-carbon power:

A. **Demand levers:** Without demand-side decarbonisation measures, the concrete and cement sector would need approximately $1,000 billion in investment simply to meet growing demand over the next 30 years and maintain existing sites. In the Net-Zero scenario, due to lower concrete and cement demand, the investment in existing and new cement production capacities will be 40% lower (by $490 billion) compared with the Base scenario.

B. **SCMs:** Unlocking SCMs requires limited investment, with approximately $30 billion invested in new grinding facilities. These investments typically reduce operational costs.

C. **Supply-side decarbonisation:** The vast majority (approximately $390 billion) of decarbonisation investments are associated with the installation of carbon capture equipment on existing cement plants, which costs an extra $150 million to $300 million per plant.[65,xxxii] More than 90% of existing plants require carbon capture. Up-front capital expenditures are expected to reduce over time as new capture technologies become available.

   These capital costs could be reduced if alternative chemistries can deliver tested and commercially viable products, thereby eliminating the need for CCU/S. Assuming capital expenditures of low-carbon chemistries are 20%–30% more expensive than traditional cement production,[xxxiii] then additional costs could be $60 million to $100 million per plant, significantly reducing the investment needed for new production.

   Switching to alternative fuels such as waste and hydrogen will require limited investment in kilns. The majority of the costs associated with kilns will be operational (e.g., for hydrogen, these include the cost of generation, which includes capital expenditures for the electrolysers and renewable electricity).

D. **Low-carbon power and CO_2 transport and storage infrastructure** represent an investment of $440 billion, dedicated to scaling carbon transport and storage networks ($175 billion) as well as low-carbon electricity and hydrogen generation ($250 billion to $300 billion).

There are significant uncertainties around these costs given the early stage of development of solutions such as carbon capture and the site-specific nature of the investments that might be required.

[xxxii] For a typical cement plant with 2.25 million tonnes cement per year. Lower range refers to the retrofit investments in 2030 for indirect calcination and the higher range refers to absorption and oxyfuel capture technologies.

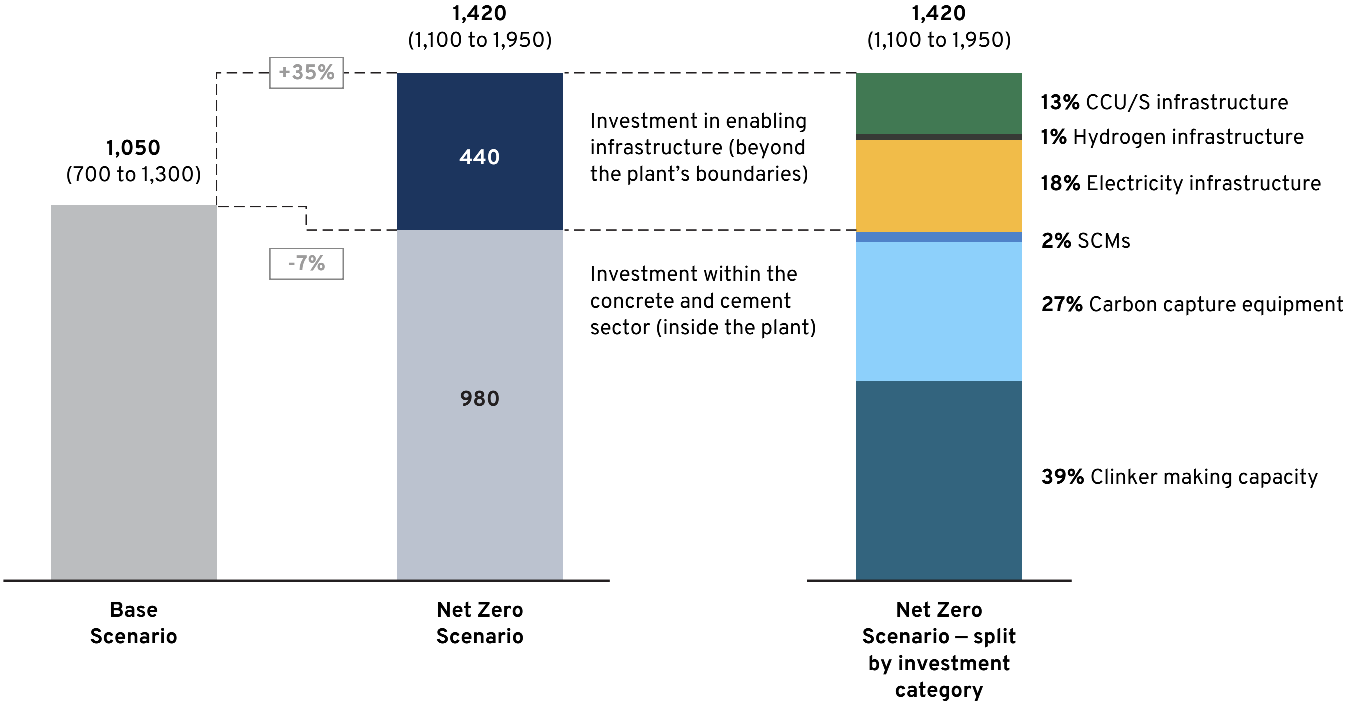
[xxxiii] Based on interviews with experts.

EXHIBIT 2.9

Delivering a Net-Zero scenario requires an investment increase of 35% compared with the base scenario, mostly driven by infrastructure requirements

Cumulative investments 2022 to 2050, $ billions, mid-point

Exhibit shows mid-point values. Technological uncertainty on global CAPEX assumptions is approximately +/-30%. Taking into account site-specific variations, the uncertainty could be significantly higher.



Source: MPP analysis (2022)

Additional investment, not quantified in the model and Exhibit 2.9, would be needed to deliver this transition, including:

- **Power grid investment:** Transmission and distribution systems will need expanding and upgrading, particularly if a large amount of CCU/S equipment is installed. Globally, this infrastructure is estimated by the ETC to cost a cumulative $36 trillion between 2020 and 2050. It is important to note that this number is not an additional cost on top of the Base scenario.[66]
- **Waste investments:** To unlock the more than 400% increase in demand for waste-derived fuels, new investments might be needed in waste processing facilities.
- **Other enablers of CCU/S:** Other enablers of CCU/S will incur capital costs, such as intermediate storage, steam generators, and other infrastructure. These are not included in this assessment.

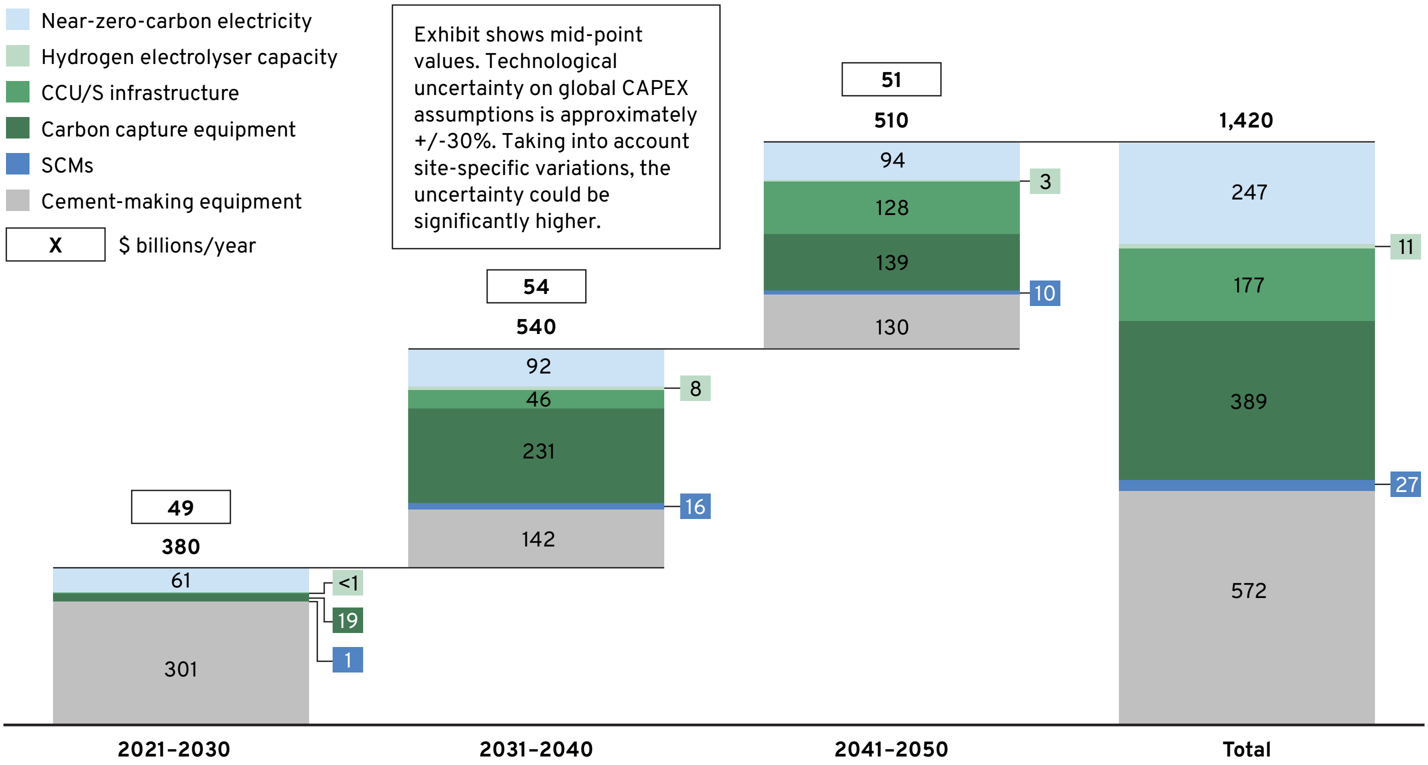
Time line of investment

To deliver the Net-Zero scenario, investment needs peak in the 2030s, with $54 billion investment per year on average to pay for the rapid build-out of carbon capture equipment across the sector, driven by the need to make significant emissions reductions from the 2030s onward (Exhibit 2.10).

EXHIBIT 2.10

Indicative total investments needed from 2022 to 2050 to deliver a net-zero sector

10-year investments for the cement sector — 1.5°C scenario, $ billions



Note: Cement-making equipment includes clinker kiln and cement grinding installations. For the carbon capture equipment, the average capital expenditure for post-combustion and oxyfuel capture technology is assumed.

Source: MPP analysis, ECRA (2022)

Sensitivities of investment needs

The pace of deployment of emerging and breakthrough technologies could impact the investment needs and operational costs of the sector. For example, alternative chemistries require new production facilities supported by increased low-carbon electricity use, which changes the investment needs in the plant and reduces the need to retrofit carbon capture equipment and access or build CCU/S infrastructure. In addition, the use of hydrogen or electricity in kilns could impact operational costs, depending on the price of locally available electricity and hydrogen.

2.2.7 Cost implications of the transition to low-carbon concrete and cement

The total green premium for net-zero concrete in the Net-Zero scenario is expected to be relatively small, increasing construction costs by a mere 1.5%–3%. These costs could potentially be offset by more efficient use of concrete in structures to reduce demand. Thus, the cost increase for end-users is small, because most costs come from the emissions-intensive clinker-making process, and clinker is only a small percentage of the overall cost of a construction project.

A future aspect of the value proposition for cement and concrete producers is that these low- and near-zero-carbon products will be sought after and valued. There is a global market opportunity for the sector from which to derive value and benefit. This is key as efforts for cement producers to cover their high initial investment and operating costs are significant, as decarbonisation levers (in a carbon capture–driven scenario) represent a 300%–400% increase in the cost of clinker and therefore a 40%–120% increase in the cost of cement. This high cost of clinker and cement production translates into a 15%–40% ($20–$40/m^3) cost increase for concrete in 2050 (Exhibit 2.11).

EXHIBIT 2.11

Without policy support, a 40–120% increase on cement costs translates into a 1.5%–3% increase in cost of construction

Percentage cost increase

*The green premium will be higher in infrastructure projects with high concrete content and global south markets.

Note: Scenario based on the Net-Zero Scenario, using 1.6 Gt of carbon capture. Ranges driven by variation in underlying product and abatement costs. The cost premium includes capex and opex.

Source: MPP analysis (2022)

Approximately 95% of the total additional costs for low-carbon concrete production comes from the significant extra capital, operational, transport, and storage costs of carbon capture (\$160–\$190/t CO_2). By contrast, other decarbonisation levers (e.g., SCMs and demand reductions) can be implemented at lower or negative costs, and hence be hidden within the cost premium.

The cost premium for zero-carbon concrete varies largely depending on the mix of decarbonisation levers and technology choice. It is particularly sensitive to the regional costs of carbon capture, as these depend heavily on the capture technology used and the underlying local cost of concrete and cement, which vary significantly by location and use of concrete. The change in costs will likely change price setting in the wider market, with location, policy changes, and supply chain evolution all likely to influence how price setting will evolve. In any case, policy support is required at the production stage of the value chain to make the transition possible.

The total cost of decarbonisation could be reduced by increasing either the cost efficiency of specific levers or uptake of more cost-effective levers where this is (technically) possible. Innovation and development of emerging technologies within these levers could also play a key role in cost. For instance, unlocking new forms of carbon capture could reduce the costs of capture by over two-thirds compared with adsorption-based capture, the leading technology available today. Additionally, the increased uptake of alternative chemistries (once they reach commercialisation) could also decrease total costs as it would decrease the need for CCU/S. Some early estimates suggest a cement cost premium of 20%–40% compared with traditional production methods,[xxxiv] which is significantly lower than the 40%–120% cost premium associated with a carbon capture–driven route.

Abatement costs for different levers

The marginal abatement cost curve (Exhibit 2.12) highlights the savings and costs expected from different levers in 2030, and the potential volume of CO_2 emissions that could be reduced if implemented. This overview illustrates that although CCU/S is critical to decarbonise the industry, it is also the least cost-efficient lever, at an abatement cost of \$160/t CO_2. By contrast, switching to alternative fuels and energy efficiency levers and savings in cement and binders is expected to lead to cost savings or be close to cost neutral in the Net-Zero scenario (−\$35–\$20/t CO_2).

[xxxiv] Early estimates of the additional costs associated with alternative chemistries from interviews with experts. Additional independent assessments of costs and performance will help determine the extent to which alternative chemistries can provide a lower-cost pathway.

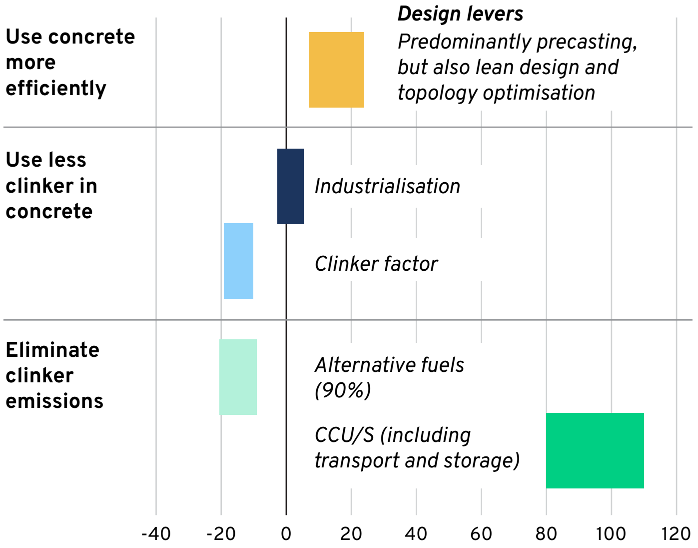
EXHIBIT 2.12

Abatement curve for the Net-Zero scenario

🟨 Efficiency in design and construction ■ Efficiency in concrete production 🟦 Savings in cement and binders 🟩 CCU/S 🟩 Switching to alternative fuels and energy efficiency

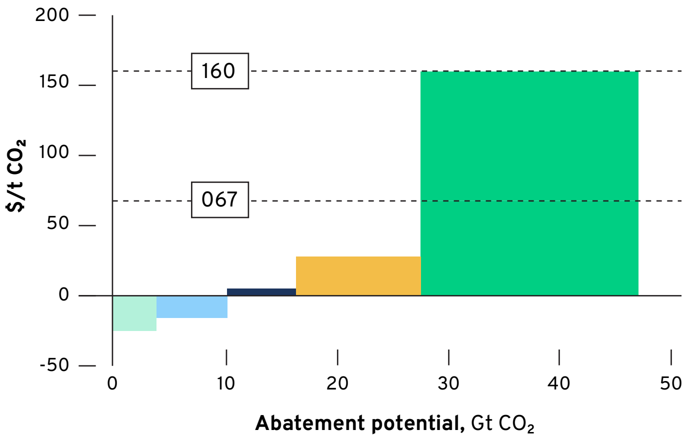
Most levers have abatement costs between –\$25/t CO_2 and \$25/t CO_2, except for carbon capture at \$160/t CO_2

Abatement cost per abatement lever in 2040, \$/t CO_2



Most emissions reductions can be achieved by a cost lower than \$25/t CO_2

Abatement curve in the Net-Zero Scenario between 2022 and 2050



Note: Levers ordered from lowest to highest abatement costs. This figure highlights global averages. Precise outputs depend on the region

Note: Figures depend on the regional circumstances; in particular, average abatement costs are lower if some measures have already been successfully applied. Industrialisation investments in ready-mix plants are largely offset by reductions in labour costs. Average levelised cost of clinker making are calculated based on the post-combustion and oxyfuel capture technology.

Source: MPP analysis, GCCA (2021), Roadmap, ECRA experts

Because efficiency measures are significantly more cost-effective than carbon capture, they should be maximised where possible.

Potential revenue streams to partially offset decarbonisation costs

The capturing of CO_2 could mean some additional income streams for cement sites:

A. **Revenue from usage of carbon:** Utilisation of carbon refers to all applications in which CO_2 is not stored in a dedicated geological storage site but embedded in a product. There are three instances when this could be more economic:

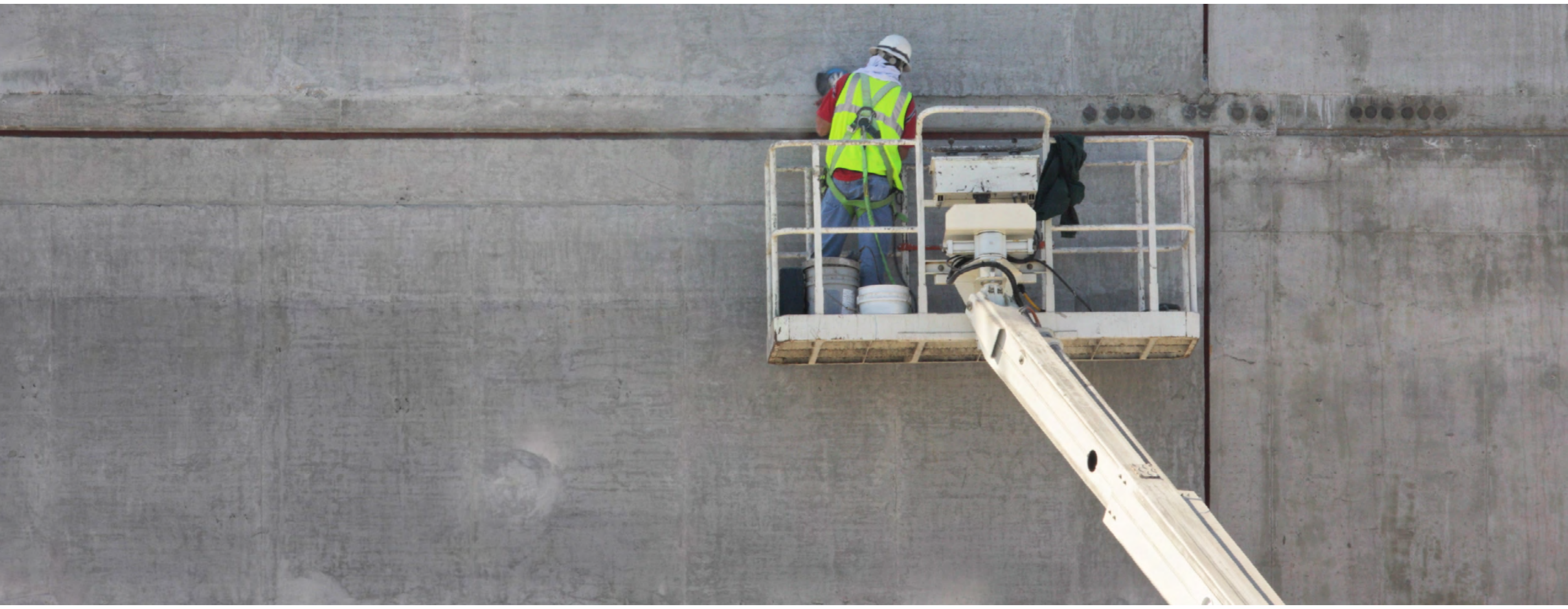
   - When the use of the captured CO_2 in a product replaces fossil fuel inputs, with product producers therefore willing to pay for the CO_2 input.
   - When the use of CO_2 improves the product so that its producer can increase its price.
   - When embedding the CO_2 in the product costs less than storing it in a geological formation.

B. **Revenue from negative emission credits:** When (a portion of) biomass is used for heating the kiln, the total emissions after carbon capture could be negative as sustainable biomass can be counted as carbon neutral, provided it meets sustainability and emissions intensity conditions. In this case, the cement producers could use these negative emissions to do internal carbon offsetting or to get a carbon credit that could be sold on the voluntary carbon market.

These potential revenue streams will be highly dependent on local conditions and evolve over time, starting relatively small, given the current market for CO_2 and current low use of biomass for cement production.

PART III

CONCLUSION: FROM STRATEGY TO ACTION



Sections 1 and 2 showed that it is possible for the concrete and cement sector to reach net zero by 2050 while also staying within the 1.5°C carbon budget if immediate joint action is taken. This section shows how to move from strategy to action through collective efforts from industry players, governments, and financial institutions to ensure a 1.5°C-aligned net-zero transition.

These three groups of actors are the focus of this report. It is, however, crucial that the sector collaborates closely with the full traditional value chain and the wider energy and carbon infrastructure sector. This section first highlights the key industry milestones for 2025 and 2030, and then details the actions needed from industry itself, governments, and financial institutions to achieve these milestones.

3.1 Key technology milestones to reach by 2030

As highlighted in Section 2, relying on just one of these three lever groups will put at risk the whole transition. Demand and efficiency levers focused on using less clinker in cement and less cement in concrete can only take the sector so far, whereas technology levers such as carbon capture require critical commercialisation and are technically complex and expensive. Therefore, the industry should achieve a certain set of milestones that cover all lever groups to achieve the net-zero transition.

Exhibit 3.1 shows the key milestones in 2025 and 2030 to get the concrete and cement sector on track to deliver the net-zero target in 2050 and stay within the sector's carbon budget. The Base scenario in this report shows that continuing business-as-usual will not bring the industry to meet these targets. Within this decade, it is therefore crucial to ramp up and commercialise near-zero-emissions cement production technology, have 33-45 operational zero-carbon plants equipped with CCU/s in 2030, deploy demand reduction levers to their fullest potential, and ensure wider energy infrastructure is in place to support the accelerated transition after 2030, as highlighted in the previous sections.

In addition, the development of innovative technologies is also important for ramping up low- and near-zero-carbon cement production before 2030 (see Box 10). Breakthrough technologies may bring cheaper CCU/S, different net-zero cement alternatives, CO_2-cured aggregates, and new SCMs to the market, which all lower the cost of transition in the long term.

EXHIBIT 3.1

Key milestones to unlock a 1.5°C-aligned, net-zero concrete and cement sector

Key milestones until 2025	Key milestones until 2030
DEMAND: Efficiency in clinker, cement, and concrete uses	
Concrete demand reduces by 4% compared with business-as-usual	Concrete demand peaks at around 38 Gt in 2030 and starts to decrease afterward
Global average clinker–binder ratio reduces to 0.61 from 0.63 today	Global average clinker–binder ratio reduces to 0.54-0.58 from 0.63 today. Regions with high SCMs availability can reach 0.5 or lower
	Share of bagged cement reduces to 20%
SUPPLY: Low- and zero-carbon concrete and cement production	
Governments permitting increased use of SCMs and use procurement power to bring about deployment	33-45 plants with carbon capture technology
Companies have developed plant-by-plant net-zero strategies	Demonstration of new technology, by implementing pilots of electric or hydrogen kilns of alternative chemistries at industrial scale
INFRASTRUCTURE: Wider energy system infrastructure	
CO_2 transport and storage plans in place and construction started across three regions	CO_2 transport and storage infrastructure operational in order to serve 33-45 plants

Source: MPP analysis

3.2 Required actions to put concrete and cement on a 1.5°C-aligned net-zero path

Achieving the milestones set out in the previous section requires addressing three key challenges:

1. **Accelerating the adoption of low-carbon methods and technologies in the concrete and cement sector**
2. **Bridging the cost differential and creating demand for low- and zero-carbon concrete**
3. **Ensuring supporting infrastructure (particularly carbon transport and storage) is scaled rapidly**

Exhibit 3.2 summarises the key actions that the concrete and cement value chain, policymakers, and financial institutions need to take for concrete and cement to become a net-zero, 1.5°C-aligned sector.

EXHIBIT 3.2

Summary of high-potential solutions to address the three key challenges to decarbonise the sector

🟨 Action from supply side industry players
🟥 Action from both the supply and demand side industry players

CHALLENGES	HIGH-POTENTIAL SOLUTIONS	KEY ACTORS			EXAMPLES
		Industry	Policy	Finance	
Accelerating the adoption of low-carbon methods and technologies in the concrete and cement sector	Research and development, particularly for early-stage technologies	🟨	🟨	🟨	Government loans, research contracts
	Performance-based cement and concrete standards supported by robust testing measures	🟥	🟨		Standards based on strength and durability, instead of prescriptive requirements on clinker content
	Plant-level pathways to achieve net-zero targets and interim milestones	🟨			
	Standardised definition and accounting methods for zero-emissions cement and concrete		🟨		
	Policy mandate on the reuse and recycling of concrete		🟨		
	Policy mandates or incentives to accelerate the market structural change from bagged to bulk cement	🟥	🟨		
Bridging the cost differential and creating demand for low- and zero-carbon concrete	Expanded use of Environment Product Declaration (EPD)	🟥	🟨		Open EPD database such as the EC3 tool; reduce the cost burden for manufacturers to get EPD
	Off-take agreements for breakthrough projects			🟨	
	Education, awareness, and training programs for producers and consumers	🟥			
	Green public and private procurement programs for concrete	🟥	🟨		IDDI green public procurement pledge; ConcreteZero; First Movers Coalition; US Federal Buy Clean Initiative
	Fiscal incentives on zero-emissions cement-making technology adoption, including taxes, cap-and-trade system, and subsidies		🟨	🟨	Carbon Border Adjustment Mechanism; 45Q tax credits for CCU/S
	Sufficient capital to support the initial development of investment intensive levers, potentially through blended financing	🟨	🟨	🟨	
Ensuring supporting infrastructure is scaled rapidly	Standards, market regulations, and infrastructure for CCU/S	🟨	🟨	🟨	Streamlining the permitting process for CCU/S
	Development of industrial hubs with shared infrastructure among hard-to-abate sectors		🟨	🟨	Los Angeles and Houston industrial hubs supported by MPP
	Supply chain for new SCMs	🟨			

Note: “Key actors” refers to the main initiator of the action. Collaboration along the value chain is key.

Source: MPP Analysis

3.2.1 Required industry actions in this decade

The industry's journey to net zero requires all links in the concrete and cement value chain to take decisive action, be they cement manufacturers, concrete producers, developers, designers, or structural engineers. Increased coordination and collaboration across the value chain helps align incentives for decarbonisation, improve information transparency and awareness of low-carbon materials, and accelerate the implementation of decarbonisation levers. The specific actions industry can take are detailed in Exhibit 3.3. In general, industry actors play a role in solving all three key challenges:

A. **The concrete and cement value chain can accelerate the adoption of low-carbon methods and technologies in the concrete and cement sector.**

- **Research and development:** Many of the options for reducing the cost of decarbonising production rely on new and emerging technologies. **Industry action to develop these technologies should include:**
    - Researching and testing breakthrough technologies that will accelerate the transition to net zero
    - Expanding training and development programmes to grow the engineering capacity needed to deliver the required scale of the net-zero transition
- **Targets and standards:**
    - Set robust corporate targets for both near- and long-term emissions reductions and identify key actions to reach the targets. Such targets need be 1.5ºC aligned, reach net-zero emissions by 2050, and be kept current to meet the expectations of investors, customers, and policymakers. Long-term CO_2 data collection will be an essential supplement to this. For example, companies should set emissions-reduction pathways that align with SBTi.
    - Develop plant decarbonisation pathways supported by robust technoeconomic analysis that align with the emissions-reduction targets.
    - Actively participate in developing performance-based standards and associated testing measures.
- **Investment:** Invest in low- and zero-carbon concrete and cement capacity in the upcoming investment cycle, including but not limited to new SCMs, ready-mix plants to accelerate the transition from bagged to bulk cement, alternative fuels, more efficient kilns technologies, and CCU/S.

B. **The concrete and cement value chain can bridge the cost differential and create demand for low- and zero-carbon concrete.**

- **Procurement programmes**:
    - Form or join a buyer's alliance for low- or zero-emissions concrete, such as the First Movers Coalition and Concrete Zero.
    - Mainstream the use of labelling concrete and cement products with the Environment Product Declaration that can be used as a standard emissions evaluation tool in private and public procurement programmes.
- **Education and awareness:** Educate downstream stakeholders on zero-emissions concrete products, including their performance, environmental benefits, usage, limitations, and costs.
- **Off-take agreements**: Agree to long-term off-take agreements with a price premium that is proportional to the incremental production cost increase and associated risks for both suppliers and buyers. Buyers with robust upstream Scope 3 targets represent critical first movers in this space.

C. **Together with other heavy-industry sectors, the concrete and cement value chain can ensure supporting infrastructure (particularly carbon transport and storage) is scaled rapidly.**

- **Industrial hubs:** Use existing infrastructure from industrial clusters in local areas and identify common needs and resources with other industry actors (e.g., sharing and collaboratively acquiring CO_2 transport, low-carbon power and hydrogen, industrial wastes for SCMs, and common raw materials). For example, MPP is working on industrial hubs in California and Houston in the United States to accelerate the transition through shared infrastructure and resources. Dispersed sites should also be included in regional plans for carbon storage and transport infrastructure.
- **CO_2 storage capacity:** Identify, access, and develop CO_2 storage capacity to ensure availability of storage sites.
- **Supply chains for SCMs:** Provide supply chain for new SCMs, such as the mining and transport of calcined clay, for example to manufacture LC3 cement.

EXHIBIT 3.3

Roles and key actions of different industry players

Industry player	Key actions to 2030
Cement plant owners	Set robust corporate targets for both near- and long-term emissions reductions and identify key actions to reach the targets Increase research and development for alternative fuels and CCU/S to commercialise after 2030 Expand the use of traditional and alternative SCMs
Concrete companies	Expand the use of traditional and alternative SCMs Increase the capacity at ready-mix plants to accelerate the transition from bagged to bulk cement
Equipment suppliers	Work with clinker producers to bring equipment for alternative fuels, new SCMs, and kiln electrification to the market
CCU/S developers	Work with clinker producers to identify the need for CCU/S infrastructure
Structural engineers	Integrate embodied carbon as a design constraint and explore different design options with lowest embodied carbon Understand performance-based concrete and cement standards to specify materials and set performance requirements of mix design
Architects	Design buildings with embodied emissions as a key design criteria, and play a role educating the building value chain in low carbon construction practices
Builders	Source the materials and works alongside suppliers to ensure the mix properties meet project needs
Concrete and cement buyers (e.g., real estate companies, departments of highway and transportation)	Make low-carbon commitments and targets, through buyers' alliances for low-carbon concrete

Source: MPP Analysis

3.2.2 Required government actions

Decisive policy action will be needed to address all three key challenges. Policymakers have a critical role in unlocking decarbonisation of the sector as they regulate products through building standards and are a key customer for buildings and infrastructure. An enabling environment – one that, for instance, supports and incentivises demand reduction levers and enables progress to the adoption of CCU/S and other technologies – is crucial in the upcoming decades. Policy actions must also start offering clear signals to producers and the wider construction industry to enable delivery of needed design, efficiency, and technology deployments over the coming decade.

Policy is important for each of the three key challenges:

A. **Policymakers can accelerate the adoption of low-carbon methods and technologies in the concrete and cement sector.**

   - **Standards:** Standards can support the deployment of new methods. Action by policymakers should focus on:
     - Identifying and reforming restrictive construction codes that hinder decarbonisation in large capital projects
     - Updating existing prescriptive standards to allow for larger SCM adoption and deployment of new cement chemistries, and in the meantime, developing performance-based concrete and cement standards supported by robust testing measures (see Box 9 for more details)
     - Standardising measurement and reporting/monitoring practices for embodied carbon in buildings or infrastructure and other use cases for concrete and cement and incorporating these into building codes (this provides a basis for further action)
     - Defining clear sustainability standards for biogenic waste supply that cover the full supply chain, are specific to each type of biogenic waste, and are specific enough to enable effective implementation and enforcement

- **Research and development:** Many of the options for decarbonising production can be streamlined and made more cost-effective with new and emerging technology. Policy action to further develop these technologies should include:

    - Providing support for early-stage research, development, and deployment of CCU/S, hydrogen, material innovation, and other breakthrough technologies through loans, fiscal incentives, contracted research, and so on. This should include assessing the life-cycle impacts of new technologies as well as preparing them for deployment.

    - Supporting the education and training of local masons and contractors, who may be unaware of the environmental implications of cement use and how to optimise materials use and reduce their projects' carbon footprints.

B. Policymakers can bridge the cost differential and create demand for low- and zero-carbon concrete.

- **Procurement programmes:** The public sector is responsible for 40%–60% of concrete volume purchased,[67] through infrastructure, housing, and other programmes. Policy action includes the following (with more specific actions highlighted in **MPP's previous publication,** *Low-Carbon Concrete and Construction: A Review of Green Public Procurement Programmes*):

    - Developing and adopting green public procurement programmes for low- and zero-emissions concrete. Green public procurement policies should have both project- and material-level emissions-reduction baselines and targets to ensure material efficiency improvements are taken into consideration.

    - Permitting the increase of SCM content in procurement programmes, as this could significantly decrease demand for and therefore emissions from clinker.

    - Setting maximum embodied carbon emissions in concrete that increase over time, providing a long-term market for low-carbon concrete. For example, RMI's roadmap for federal buildings in the US recommends an embodied carbon target for concrete in US federal building projects under the federal Buy Clean policy.[68]

- **Fiscal instruments:** Adopt appropriate market-based mechanisms based on the maturity of technology and the socioeconomic conditions, while ensuring end-goal clarity and policy consistency, such as through tax incentives, loans and subsidies, carbon taxes, and trading systems (e.g., cap and trade). For example, governments could:

    - Implement local or regional carbon pricing with border adjustment mechanisms, targeting \$75–\$100/t CO_2 in 2030.[69]

    - Include the cement sector in carbon trading programmes. For instance, China, which is responsible for producing more than 50% of the world's cement in 2020, has announced it will expand the national Emissions Trading Scheme to cover the cement sector.[70]

- **Blended financing:** Providing technology-agnostic blended financing to first-of-a-kind net-zero cement projects along with the private sector to de-risk the investment. Deployment finance should also be incentivised to accelerate infrastructure scale-up.

C. Policymakers can ensure supporting infrastructure (particularly carbon transport and storage) is scaled rapidly.

- **Standards and market regulation for CCU/S:** Clear market regulation and (measurement) standards for CCU/S are needed to ensure an investable market environment. This includes the creation of a robust legal and regulatory framework for CO_2 storage and carbon accounting (e.g., standards highlighting what forms of carbon usage are and are not considered net zero).

- **Coordination of infrastructure plans:** Policymakers should enable and incentivise the coordination of industry and other potential users of shared CCU/S and hydrogen infrastructure.

- **Non-clustered industry:** Support the development of technology and planning for sites that may not have easy access to a CO_2 transportation and storage network.

- **Grid decarbonisation:** Accelerate the transition to a zero-emissions electricity system through policy mandates and fiscal incentives (e.g., by setting clean energy adoption targets for the cement industry or initiating a mandatory coal phaseout time line).

BOX 9

The role of concrete and cement standards in decarbonising the sector

Concrete and cement are regulated by standards in all major markets. These standards usually define cement types by prescribing minimum clinker factor and maximum SCM content. Well-defined standards can ensure that a higher SCM content leads to safe, reliable, and durable concrete and cement.

The current prescriptive standards allow for higher SCM content than global averages. Within the constraints of the standards, the deployment of SCM is determined by client and project designer specification and contractor procurement. Often, when clients and designers specify the use of low (or zero) percent SCM content, it is unwarranted for technical reasons and is based on tradition, habit, or copying over specifications from previous projects. Policy incentives, including procurement programmes, to incentivise behavioural changes can stimulate greater use of SCM.

However, the existing prescriptive standards can also be a barrier to cement industry innovations because products with even lower clinker content or alternative chemistries do not comply with the materials and percentages required in these standards. Performance-based standards provide a viable solution to this barrier. Instead of specifying the clinker and SCM contents, these standards include requirements for key performance indicators such as strength, durability, workability, sulphate attack, and others.

Performance-based standards can help bring cement with high SCM content and alternative chemistries to the market, while ensuring the strength and durability of the concrete product. The introduction of such standards is contingent on establishing:

- **Clear definitions of what ‘performance’ means** (for example, strength and durability but also shrinkage and other characteristics)
- **A workable performance-testing regime** that can be applied at project level. In particular, developing robust testing measures on concrete durability throughout its service lifetime in a lab environment.

Updating the current standards requires research and a consultation process in order to create trust in the standards from the whole value chain and to ensure risks are well known and can be mitigated where possible.

It is important to start the development of performance-based testing measures and standards starting as soon as possible, and in the meantime, accelerate the adoption of SCMs under the current standards framework and update existing standards to allow faster adoption of SCMs and new technologies. The United States is an example where prescriptive and performance-based cement standards coexist. Although the performance-based ASTM C1157 does not include comprehensive testing measures, it has started to provide an alternative route for low-carbon cement innovators to enter the market.

3.2.3 Required actions from financial institutions

As shown in Section 2, $49 billion of investment will be needed every year from now to 2030 and $54 billion per year from 2031 to 2040 to unlock the net-zero transition. In this decade, 80% of the investment focuses on cement-making equipment, whereas 45% of the investment needed in the next decade is for CCU/S infrastructure. The scale of the cross-value-chain investment creates an enormous opportunity for the financial sector, whose actors are integral to achieving financial investment decisions on low-emissions concrete projects. Financial institutions can capitalise on this opportunity and help address all three key challenges as follows:

A. **Financial institutions can accelerate the adoption of low-carbon methods and technologies in the concrete and cement sector.**

   - Unlocking investment to achieve the milestones highlighted in Exhibit 3.1:
     - Actively codeveloping strategies to manage and lower the market, credit, liquidity, operational, and policy risks of first-of-a-kind projects. Blended finance provided in part by development banks could play a key role here.
     - Providing sufficient capital to unlock at least $390 billion of investment in the concrete sector from 2022 to 2030.
   - **Avoiding investment lock-in and stranded assets:** For countries and regions where demand for concrete and cement continues to grow, it is important to ensure that the newly built facilities are designed to be low or zero emissions, which avoids locked-in emissions and saves the cost of future low-carbon renovations. Multilateral institution finance will play an important role in unlocking the initial investment for the net-zero capacity.
   - **Standards:** Continue to work with industry and regulatory bodies to adapt existing carbon accounting, auditing, and verification frameworks to develop consistent concrete sector and cross-sectoral methodologies for assessing corporate and project-level emissions performance.

B. **Financial institutions can bridge the cost differential and create demand for low- and zero-carbon concrete.**

   - **Voluntary carbon market:** Developing the methodologies and protocols required to scale a voluntary carbon market, such as standardised accounting contract terms, digital exchanges, and registries. These practices have been outlined by the Taskforce on Scaling Voluntary Carbon Markets.

C. **Financial institutions can ensure supporting infrastructure (particularly carbon transport and storage) is scaled rapidly.**

   - **Coordinated investments:** Providing sufficient capital to support coordinated investments in CCU/S and hydrogen infrastructure as well as new SCM supply chains.
   - **Business model innovation:** Together with industry, developing new commercial models such as carbon capture as a service, which can lower financing and technology costs. This can be done through replicable design or modularisation.[71]

BOX 10

Supporting innovative technologies to reach commercialisation

The actions for industry, policymakers, and financial institutions recommended above are designed to encourage the adoption of both incremental and breakthrough decarbonisation measures. However, given the lower TRL and market share of innovative low- and zero-carbon concrete and cement products, accelerating the adoption of breakthrough technologies requires a s pecial set of actions from stakeholders across the value chain. It is too early to know how technological innovations could shape the sector. However, ensuring that multiple options are available will help guard against risks of technology failure or policy failure in other technologies (for example, the policy landscape for CCU/S delivering robust investable policies only in industrial clusters).

The nature of action needed will vary by technology, but there are several critical steps to ensure that the wider framework supports the inclusion of new technologies:

Enabling regulatory environment

- Concrete and cement are regulated products. To facilitate a route to market, regulators will have to ensure that new technologies have a clear, predictable path to accreditation for use in key markets. (Policymakers and industry collaborating)
- Policymakers should actively design and implement performance-based concrete and cement standards supported by robust testing measures, which will provide a basis for innovative low-carbon concrete and cement products to enter the market. (Policymakers)

Demonstrating viability

- Government should provide support (loans, contracted research, tax incentives, etc.) for R&D of new technologies and strength and durability testing measures for performance-based standards. For example, the transition of LC3 cement from pilots to commercialisation has been supported by the Swiss Agency of Development and Cooperation. (Policymakers)
- Industry should actively test breakthrough technologies through small-scale pilots and push the high-potential options to commercialisation. (Industry)

Moving from development to deployment

- Co-funding mechanisms are crucial for first-of-a-kind projects to address first-mover risks. (Industry, policymakers, financial institutions)

- Off-take agreements will help share risks between innovators, users, and investors. (Industry, financial institutions)
- Incentivise the deployment of new technologies through private and public procurement policies, for example, including innovative low- and zero-carbon concrete in the list of approved materials in government procurement programmes.
- Education and awareness programmes among industry stakeholders and consumers will help overcome existing norms and biases. (Industry and policymakers)

The development of breakthrough technologies requires a strong enabling environment created by all parties. Performance-based standards are necessary to enable the transition, but they must be complemented by awareness and behaviour changes of manufacturers, designers, structural engineers, and consumers. Research and development sets the foundation of new technologies, but they will not lead to the deployment and commercialisation of technologies without the right financing tools. With the combination of R&D, performance-based standards, norms, and routes to financing new technology in its initial stages of deployment, innovators can have the confidence to take risks and develop new technologies and bring them to market if successful.

THE WAY FORWARD

The concrete and cement industry can and must rapidly decarbonise. A critical mass of key stakeholders has already committed to the decarbonisation transition. For example, all GCCA members, accounting for nearly 50% of global cement production, have made commitments to achieve net-zero emissions by 2050. China, the largest cement-producing country, targets peak CO_2 emissions from building materials production by 2030.[72] At least 11 cement companies go beyond their net-zero pledges and have committed science-based climate targets (SBT) well below 2°C or 1.5°C targets.

Transforming these targets into reality will require stakeholder collaborations spanning the value chain from cement kiln to buyer. The technologies required for the net-zero transition are known, and major industry players have started to implement them on pilot or large scales. The cost-effective measures of reducing demand for concrete, cement, and clinker are well positioned to be deployed as soon as possible.

However, the demand-side solution alone will not get the industry to its 2050 target. Alternative fuels and CCU/S will play a significant role after 2030 on the journey to net zero, and the preparation to make that happen should start today. In addition, breakthrough technologies across the value chain provide more decarbonisation options to the industry. The first wave of technology commercialisation will also require targeted and strategic decisions by first movers in the absence of market or technology certainty to provide the necessary proof points for the sector to transition at scale in the 2030s.

The foundations of such efforts are emerging, with a steadily growing volume of feasibility studies, risk-sharing partnerships, and pilot projects. These corporate efforts are supported by numerous collaborative initiatives that aim to create the conditions for investment in low-carbon solutions. On the supply side, SBTi has published its cement sector target-setting guidance, which helps companies set the level of ambition needed to align with the 1.5°C target. On the demand side, Concrete Zero and First Movers Coalition both create a marketplace for low- and zero-carbon concrete through green private procurement programmes. In addition, the Industrial Deep Decarbonization Initiative launched a green public procurement pledge in 2022 for governments to commit to. On the finance side, the Climate Bonds Initiative issued criteria for cement production assets and activities to be included in a Certified Climate Bond.

GCCA and its network of affiliated national and regional concrete and cement associations will actively contribute to mobilising the concrete and cement value chain to enhance the environment for investment. Industry leaders must act in collaboration across the value chain, setting up or joining industrial clusters to create infrastructure synergies and direct links between producers and off-takers. Together we can propel this committed community of stakeholders to act on the essential decisions required to deliver a sustainable future for this industry and the planet.

GLOSSARY

Abatement cost	The cost of reducing CO_2 emissions, usually expressed in US$ per tonne of CO_2.
Carbon budget	The remaining sum of global emissions that can be emitted to limit global warming to 1.5°C above preindustrial levels. This report references IPCC's SR1.5 and subsequent 2019 emissions estimates, which find that to reach the 1.5°C target with limited overshoot at 50% probability, additional emissions must be limited to 580 Gt CO_2 as of 2018, and 500 Gt as of 2020.
Carbon capture utilisation or storage (CCU/S)	The term *carbon capture* refers to the process of capturing the CO_2 produced from energy generation and industrial processes. Unless otherwise specified, direct air carbon capture is not included when using this term. The term *carbon capture and storage* refers to the combination of carbon capture with underground carbon storage, and *carbon capture and utilisation* refers to the use of captured carbon in carbon-based products in which CO_2 is sequestered over the long term (e.g., in concrete, aggregates, or carbon fibre).
Carbon price	A government-imposed pricing mechanism, the two main types of which are a tax on products and services based on their carbon intensity, or a quota system that sets a cap on permissible emissions in the country or region and allows companies to trade the right to emit carbon (e.g., as allowances). This should be distinguished from companies' use of what are sometimes called 'internal' or 'shadow' carbon prices, which are not prices or levies, but individual project screening values.
Energy or heat emissions	CO_2 emissions from burning fuels to reach the 1,450°C required for limestone calcination in the rotary kiln. The predominant fuels currently used are coal and petcoke (82%). Other fuels include natural gas (9%), industrial wastes (6%), and biogenic waste (3%). Energy/heat emissions currently account for 35% of the total CO_2 emissions in the concrete-making process. In this report, the Scope 1 and 2 emissions from these fuels are referred to as **energy or heat emissions**. The extraction of coal also leads to a (minor) amount of Scope 3 emissions.
Green hydrogen	Hydrogen produced via electrolysis using zero-carbon electricity.
Net-zero emissions/ net-zero wcarbon/ net zero	The state in which the energy and industrial system as a whole or a specific economic sector releases zero net CO_2 emissions, either because it does not produce any or because it captures and utilises or stores the CO_2 it produces. In this state ('real net zero'), the use of offsets from other sectors should be extremely limited and used only to compensate for residual emissions from carbon capture leakage, unavoidable end-of-life emissions, or remaining emissions from the agriculture sector.
Process emissions	CO_2 emissions in the clinker-making process due to limestone ($CaCO_3$) being converted to lime (CaO). This currently accounts for 53% of the total CO_2 emissions in the concrete-making process.
Recarbonation	The uptake of CO_2 from the atmosphere by concrete during its operation and end-of-life stages through a chemical reaction that is the reverse of the chemical reaction that causes CO_2 emissions in the clinker-making process.
Technology readiness levels (TRL)	The level of maturity a certain technology has reached from initial idea to large-scale, stable commercial operation. The International Energy Agency reference scale is used, with 11 TRL increments grouped into six categories: concept (TRL 1–3), small prototype (TRL 4), large prototype (TRL 5–6), demonstration (TRL 7–8), early adoption (TRL 9–10), and mature (TRL 11).

ENDNOTES

1 Global Concrete and Cement Association, *Concrete Future: The GCCA 2050 Concrete and Cement Industry Roadmap for Net Zero Concrete*, October 2021, **https://gccassociation.org/concretefuture/wp-content/uploads/2021/10/GCCA-Concrete-Future-Roadmap-Document-AW.pdf**; and European Cement Research Academy, ed., The ECRA Technology Papers 2022 – State of the Art Cement Manufacturing – Current Technologies and their Future Development, Duesseldorf, 2022, **https://ecra-online.org/research/technology-papers**.

2 Global Concrete and Cement Association, **Concrete Future: The GCCA 2050 Concrete and Cement Industry Roadmap for Net Zero Concrete**, October 2011, **https://gccassociation.org/concretefuture/wp-content/uploads/2021/10/GCCA-Concrete-Future-Roadmap-Document-AW.pdf**.

3 International Energy Agency, 'Cement,' **https://www.iea.org/reports/cement**.

4 International Energy Agency, *Net Zero by 2050*, **https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf, May 2021.**

5 Energy Transitions Commission, *Bioresources within a Net-Zero Emissions Economy*, July 2021, **https://www.energy-transitions.org/publications/bioresources-within-a-net-zero-economy/**.

6 Material Economics, *Industrial Transformations 2050*, April 2019, **https://materialeconomics.com/publications/industrial-transformation-2050**.

7 Mineral Products Association, VDZ, and Cinar Ltd., *Options for Switching UK Cement Production Sites to Near Zero* CO_2 *Emission Fuel: Technical and Financial Feasibility*, 2019.

8 Energy Transitions Commission, *Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but Limited*, July 2022.

9 European Cement Research Academy, ed. T*he ECRA Technology Papers 2022 – State of the Art Cement Manufacturing – Current Technologies and their Future Development. Duesseldorf*, 2022, **https://ecra-online.org/research/technology-papers**.

10 ECRA, The ECRA Technology Papers 2022.

11 Global Concrete and Cement Association, *Concrete Future: The GCCA 2050 Concrete and Cement Industry Roadmap for Net Zero Concrete*, October 2021, **https://gccassociation.org/concretefuture/wp-content/uploads/2021/10/GCCA-Concrete-Future-Roadmap-Document-AW.pdf.**

12 Climeworks, *Deep Decarbonization Pathways for the Concrete and Cement Cycle in the United States, India, and China*, March 2021, **https://www.climateworks.org/report/decarbonizing-concrete/.**

13 Various: Material Economics Industrial Transformation 2050, Cembureau 2021 Activity Report, WBCSD Low Carbon Technology Roadmap for the Indian Cement Sector: Status Review 2018, Climate Works Decarbonizing Concrete.

14 MPP analysis of GCCA Roadmap.

15 Hannah Ritchie, Max Roser, and Pablo Rosado, 'CO_2 and Greenhouse Gas Emissions,' 2020, accessed December 2022, **https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions**.

16 BizVibe, 'Global Cement Industry Outlook 2020,' accessed January 2023, **https://blog.bizvibe.com/blog/top-10-cement-companies-world;** GCD - Global Cement Directory, GlobalCement, 2022.

17 International Energy Agency, 'Cement,' accessed October 2022, **https://www.iea.org/reports/cement**.

18 International Energy Agency, 'Cement,' accessed October 2022, **https://www.iea.org/reports/cement**.

19 International Energy Agency, *Net Zero by 2050*, **https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.**

20 Average lifetime of cement kilns. Cembureau The European Cement Association (2018), Thermal Energy Efficiency accessed at **https://lowcarboneconomy.cembureau.eu/5-parallel-routes/energy-efficiency/thermal-energy-efficiency/**.

21 A. Marmier, *Decarbonisation Options for the Cement Industry*, EUR 31378 EN, Publications Office of the European Union, Luxembourg, 2023, ISBN 978-92-76-61599-6, doi:10.2760/174037, JRC131246.

22 European Cement Research Academy, ed. The ECRA Technology Papers 2022 – State of the Art Cement Manufacturing – Current Technologies and their Future Development. Duesseldorf, 2022, **https://ecra-online.org/research/technology-papers.**

23 Global Concrete and Cement Association, *Concrete Future: The GCCA 2050 Concrete and Cement Industry Roadmap for Net Zero Concrete*, October 2021, **https://gccassociation.org/concretefuture/wp-content/uploads/2021/10/GCCA-Concrete-Future-Roadmap-Document-AW.pdf.**

24 S. Teske, One Earth Climate Model, 2022.

25 Energy Transitions Commission, *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonization to Keep 1.5°C Alive*, March 2022, **https://www.energy-transitions.org/wp-content/uploads/2022/03/ETC-CDR-Report-Mind-the-Gap.pdf**.

26 Summarized from numerous sources: UN, Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry, Material Economics Industrial Transformation 2050, ICE Low Carbon Concrete Routemap, IEA Material efficiency in clean energy transitions, IEA Energy Technology Perspectives 2020, Chatham House Report Making Concrete Change.

27 International Energy Agency (2022), ETP Clean Energy Technology Guide.

28 Energy Transitions Commission, *Bioresources within a Net-Zero Emissions Economy*, July 2021, **https://www.energy-transitions.org/publications/bioresources-within-a-net-zero-economy/**.

29 Material Economics, *Industrial Transformations 2050*, April 2019, **https://materialeconomics.com/publications/industrial-transformation-2050**.

30 Systemiq supported by Laudes Foundation, Efficient and Balanced Space Use: Shaping Vibrant Neighbourhoods and Boosting Climate Progress in Europe, 2022.

31 United Nations Environment Programme, *Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO_2 Cement-based Materials Industry*, 2017, **https://wedocs.unep.org/handle/20.500.11822/25281.**

32 Material Economics, *Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry*, 2019, **https://materialeconomics.com/publications/industrial-transformation-2050.**

33 Institution of Civil Engineers Knowledge Hub, Low Carbon Concrete Routemap, 2022, **https://www.ice.org.uk/engineering-resources/briefing-sheets/low-carbon-concrete-routemap/.**

34 International Energy Agency, *Material Efficiency in Clean Energy Transitions*, 2019, **https://www.iea.org/reports/material-efficiency-in-clean-energy-transitions; and** International Energy Agency, *Energy Technology Perspectives*, September 2020, **https://www.iea.org/reports/energy-technology-perspectives-2020.**

35 Chatham House, *Making Concrete Change: Innovation in Low-Carbon Concrete and Cement*, June 2018, **https://www.chathamhouse.org/2018/06/making-concrete-change-innovation-low-carbon-cement-and-concrete.**

36 Chatham House, *Making Concrete Change: Innovation in Low-Carbon Concrete and Cement*, June 2018, **https://www.chathamhouse.org/2018/06/making-concrete-change-innovation-low-carbon-cement-and-concrete**.

37 J. Giesekam, *Construction Sector Views on Low Carbon Building Materials*, July 2015, **https://www.tandfonline.com/doi/full/10.1080/09613218.2016.1086872.**

38 Expert interview, 2022.

39 European Cement Research Academy, ed., The ECRA Technology Papers 2022 – State of the Art Cement Manufacturing – Current Technologies and their Future Development, Duesseldorf, 2022, **https://ecra-online.org/research/technology-papers**.

40 Ecocem, *Raising Ambitions Reducing Emissions*, November 2022, accessed XXX, **https://www.ecocemglobal.com/news-insights/cement-raising-ambitions**.

41 K. Scrivener and L. Vanderley, United Nations Environment Programme, *Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO_2 Cement-based Materials Industry*, 2018.

42 K. Scrivener and L. Vanderley, United Nations Environment Programme, *Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO_2 Cement-based Materials Industry*, 2018.

43 MPP, *Emerging Market Cement Decarbonisation*, 2022, **https://missionpossiblepartnership.org/wp-content/uploads/2022/10/emerginmarketcementdecarbonization.pdf**.

44 *Material Economics, Industrial Transformation 2050 – Pathways to Net-Zero Emissions from EU Heavy Industry*, 2019, **https://materialeconomics.com/publications/industrial-transformation-2050.**

45 K. Scrivener and L. Vanderley, United Nations Environment Programme, *Eco-efficient Cements: Potential Economically Viable Solutions for a Low-*CO_2 *Cement-based Materials Industry*, 2018.

46 European Cement Research Academy, ed., The ECRA Technology Papers 2022 – State of the Art Cement Manufacturing – Current Technologies and their Future Development, Duesseldorf, 2022, **https://ecra-online.org/research/technology-papers**.

47 European Cement Research Academy, ed., The ECRA Technology Papers 2022 – State of the Art Cement Manufacturing – Current Technologies and their Future Development, Duesseldorf, 2022, **https://ecra-online.org/research/technology-papers**.

48 A. Hasanbeigi and C. Springer, *California's Cement Industry: Failing the Climate Challenge*, Global Efficiency Intelligence, 2019, **https://www.climateworks.org/wp-content/uploads/2019/02/CA-Cement-benchmarking-report-Rev-Final.pdf;** A. Marmier, *Decarbonisation Options for the Cement Industry*, EUR 31378 EN, Publications Office of the European Union, Luxembourg, 2023, ISBN 978-92-76-61599-6, doi:10.2760/174037, JRC131246.

49 IPCC, *Guidelines for National Greenhouse Gas Inventories*, Volume 2, 2006, **https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf**.

50 IFC, *Increasing the Use of Alternative Fuels at Cement Plants: International Best Practice*, 2017, **https://www.ifc.org/wps/wcm/connect/33180042-b8c1-4797-ac82-d5167689d39/Alternative_Fuels_08+04.pdf?MOD=AJPERES&CVID=lT3Bm3Z.**

51 Mineral Products Association, VDZ, and Cinar Ltd., *Options for Switching UK Cement Production Sites to Near Zero* CO_2 *Emission Fuel: Technical and Financial Feasibility*, 2019.

52 Global Concrete and Cement Association, *Concrete Future: The GCCA 2050 Concrete and Cement Industry Roadmap for Net Zero Concrete*, October 2021, **https://gccassociation.org/concretefuture/wp-content/uploads/2021/10/GCCA-Concrete-Future-Roadmap-Document-AW.pdf.**

53 IPCC, *Guidelines for National Greenhouse Gas Inventories*, Volume 2, 2006, **https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf**.

54 RMI, *Towards Carbon Neutrality for China's Cement Industry*, 2022.

55 European Cement Research Academy, ed., The ECRA Technology Papers 2022 – State of the Art Cement Manufacturing – Current Technologies and their Future Development, Duesseldorf, 2022, **https://ecra-online.org/research/technology-papers**.

56 WBCSD, CO_2 *and Energy Accounting and Reporting Standard for the Cement Industry*, May 2011, **https://www.wbcsd.org/Sector-Projects/Cement-Sustainability-Initiative/Resources/CO2-Accounting-and-Reporting-Standard-for-the-Cement-Industry.**

57 Energy Transitions Commission, *Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but Limited*, July 2022, **https://www.energy-transitions.org/new-report-vital-but-limited-role-for-ccus-to-deliver-a-net-zero-economy/**.

58 European Cement Research Academy, ed., The ECRA Technology Papers 2022 – State of the Art Cement Manufacturing – Current Technologies and their Future Development, Duesseldorf, 2022, **https://ecra-online.org/research/technology-papers**.

59 Energy Transitions Commission, *Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but Limited*, July 2022, **https://www.energy-transitions.org/new-report-vital-but-limited-role-for-ccus-to-deliver-a-net-zero-economy/**.

60 Energy Transitions Commission, *Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but Limited*, July 2022, **https://www.energy-transitions.org/new-report-vital-but-limited-role-for-ccus-to-deliver-a-net-zero-economy/.**

61 Energy Transitions Commission, *Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but Limited*, July 2022, **https://www.energy-transitions.org/new-report-vital-but-limited-role-for-ccus-to-deliver-a-net-zero-economy/.**

62 European Cement Research Academy, ed., *The ECRA Technology Papers 2022 – State of the Art Cement Manufacturing – Current Technologies and their Future Development*, Duesseldorf, 2022, **https://ecra-online.org/research/technology-papers**.

63 Global Concrete and Cement Association, *Concrete Future: The GCCA 2050 Concrete and Cement Industry Roadmap for Net Zero Concrete*, October 2021, **https://gccassociation.org/concretefuture/wp-content/uploads/2021/10/GCCA-Concrete-Future-Roadmap-Document-AW.pdf**

64 European Cement Research Academy, ed., *The ECRA Technology Papers 2022 – State of the Art Cement Manufacturing – Current Technologies and their Future Development*, Duesseldorf, 2022, **https://ecra-online.org/research/technology-papers**.

65 European Cement Research Academy, ed., The ECRA Technology Papers 2022 – State of the Art Cement Manufacturing – Current Technologies and their Future Development, Duesseldorf, 2022, **https://ecra-online.org/research/technology-papers**.

66 Energy Transitions Commission, *Making Clean Electrification Possible: 30 Years to Electrify the Global Economy*, April 2021, **https://www.energy-transitions.org/publications/making-clean-electricity-possible/#download-form.**

67 MPP, *Low-Carbon Concrete and Construction: A Review of Green Public Procurement Programmes*, 2022, **https://missionpossiblepartnership.org/wp-content/uploads/2022/06/LowCarbonConcreteandConstruction.pdf**.

68 RMI, *Roadmap to Reaching Zero Embodied Carbon in Federal Building Projects*, 2022, **https://rmi.org/insight/roadmap-to-reaching-zero-embodied-carbon-in-federal-building-projects/**.

69 Anita Hafner, Peter Janoska, and Caroline Lee, "The importance of real-world policy packages to drive energy transitions," IEA, July 2018, **https://www.iea.org/commentaries/the-importance-of-real-world-policy-packages-to-drive-energy-transitions**.

70 Asia Financial, 'China Carbon Market Expansion Delayed – Caijing,' 2022, accessed January 2023, **https://www.asiafinancial.com/china-carbon-market-expansion-delayed-caijing.**

71 Energy Transitions Commission, *Carbon Capture, Utilisation & Storage in the Energy Transition: Vital but Limited*, July 2022, **https://www.energy-transitions.org/new-report-vital-but-limited-role-for-ccus-to-deliver-a-net-zero-economy/.**

72 Chinese Government, Building Materials Industry Carbon Peak Implementation Plan, 2022, **https://www.gov.cn/zhengce/zhengceku/2022-11/08/5725353/files/7277f2cc48d14d6696a240fb748eb49c.pdf**.

Disclaimer

This effort benefitted from the input of a number of organisations who were consulted on the model inputs and architecture and endorse the general thrust of the arguments made in this report but should not be assumed to agree with every finding, calculation or recommendation. There are significant risks and uncertainties, particularly related to cost, performance, and rate of implementation for technologies, the actions of governments, political conditions, exposure to other sectors, the timing and amount of government funding, availability of low emission materials, and other unforeseeable events, including technologies that are not actually proven, and actual results may differ materially from those indicated by these forward-looking assumptions and statements, which, in some cases, can be identified by the use of forward-looking words such as “may,” “assume,” “might,” “should,” “could,” “continue,” “would,” “can,” “consider,” “anticipate,” “estimate,” “expect,” “envision,” “plan,” “believe,” “foresee,” “predict,” “potential,” “target,” “strategy,” “intend,” “aimed” or other similar terms. These forward-looking assumptions and statements reflect, as of the date such forward-looking statements are made, or unless otherwise indicated, current expectations and projections about future events based on knowledge of present facts and circumstances and assumptions about future events. These statements necessarily involve risks and uncertainties that could cause actual results to differ materially from the expectations outlined in this report, which include, but are not limited to uncertainties, costs, performance and rate of implementation of technologies, some of which are yet not proven, among many other risks and uncertainties that affect the cement and concrete industry.

MISSION POSSIBLE PARTNERSHIP

The Mission Possible Partnership is an alliance of climate leaders focused on supercharging efforts to decarbonise some of the world's highest-emitting industries in the next 10 years.