MAKING NET-ZERO CONCRETE AND CEMENT POSSIBLE

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

EXECUTIVE SUMMARY / 2023

MISSION POSSIBLE PARTNERSHIP

Founded by

Energy Transitions Commission

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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.

ACKNOWLEDGEMENTS

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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).

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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**.

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.

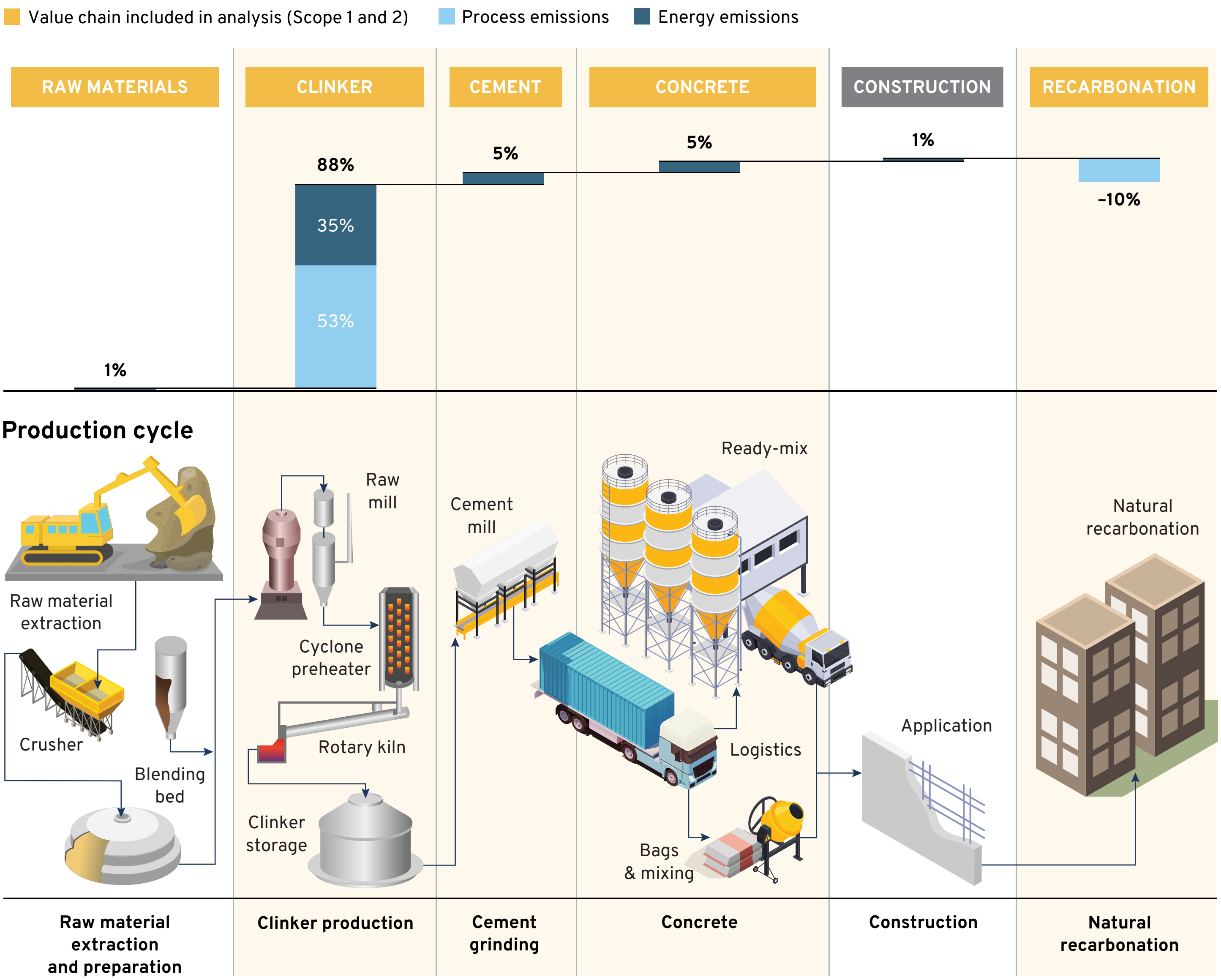
3. **Significant projected demand growth:** Global cement production capacity increased by 30% in the last decade.[3] With no further action, demand for cement is expected to grow by 14% from 2020 to 2030, and another 22% by 2050, driven by population growth and economic development in Global South countries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

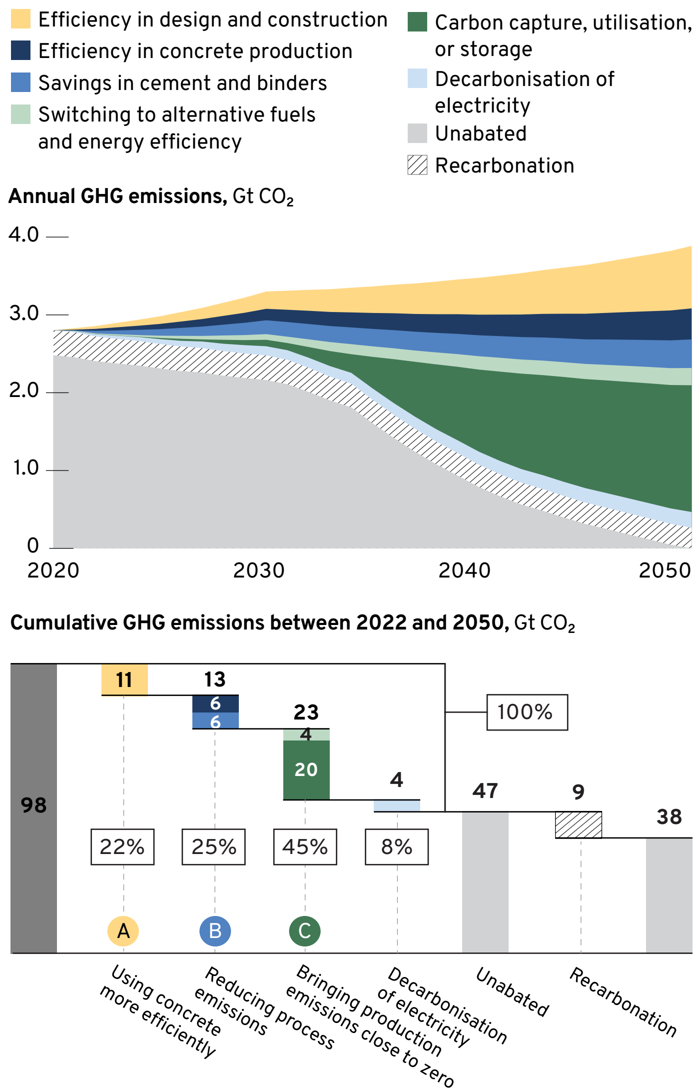
C. **Bringing production emissions close to zero,** by:

- **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.

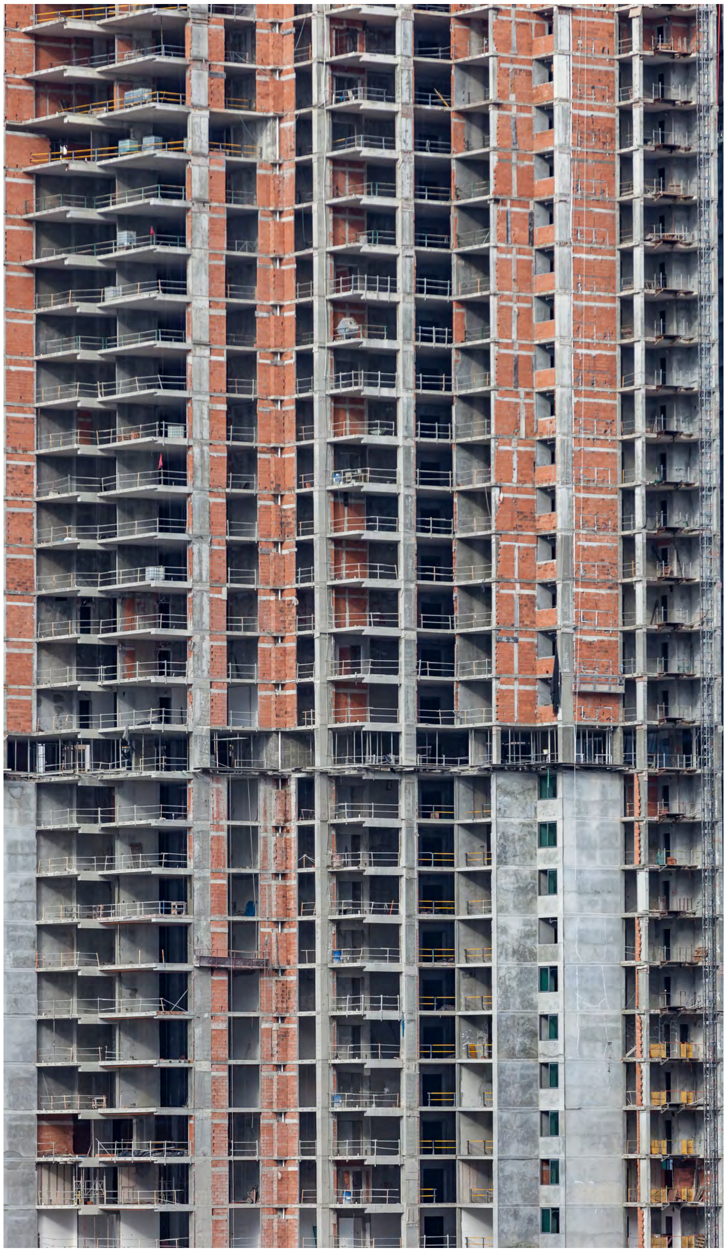


EXHIBIT D

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).

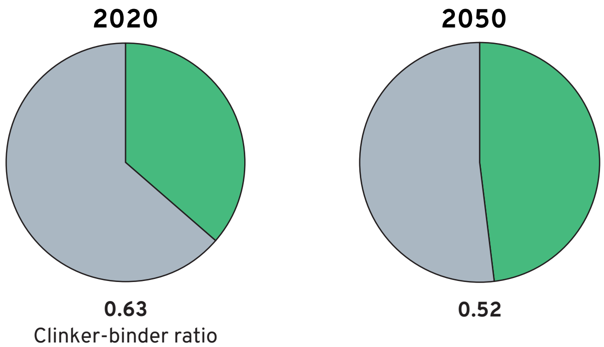
EXHIBIT E

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 ...

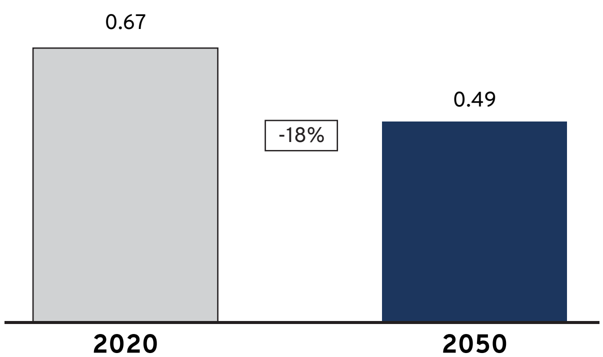
CEMENT COMPOSITION

Average cement mix Clinker SCMs



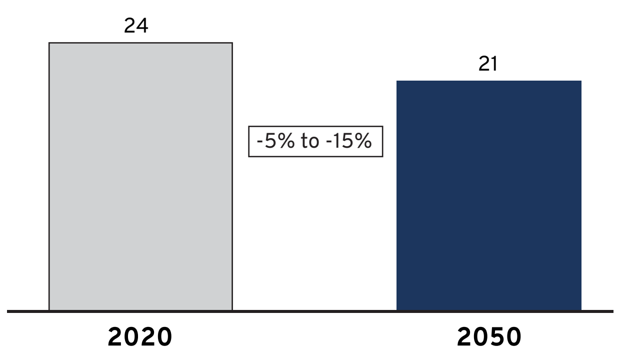
EMISSIONS

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



COSTS

$/t cement, cost reductions depend on SCMs used



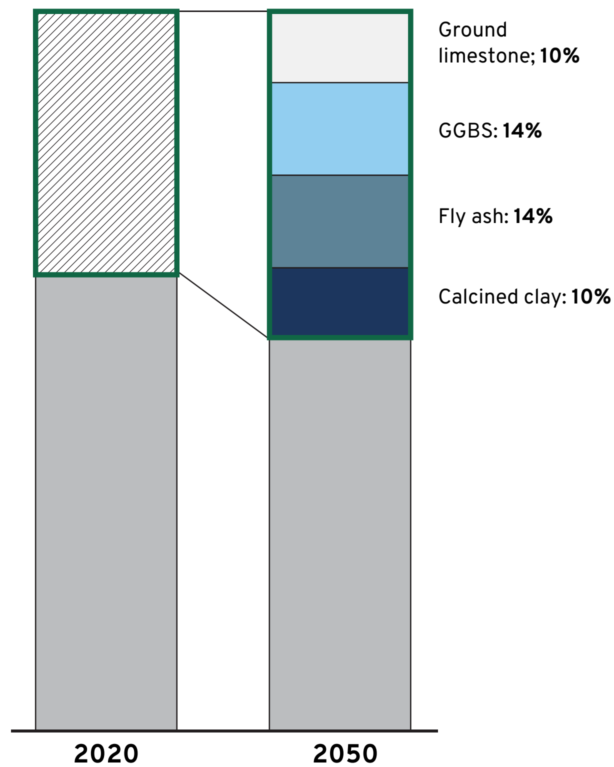
Note: SCM availability is on a global level compared with limestone.

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

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

GLOBAL CEMENT MIX

% of mass



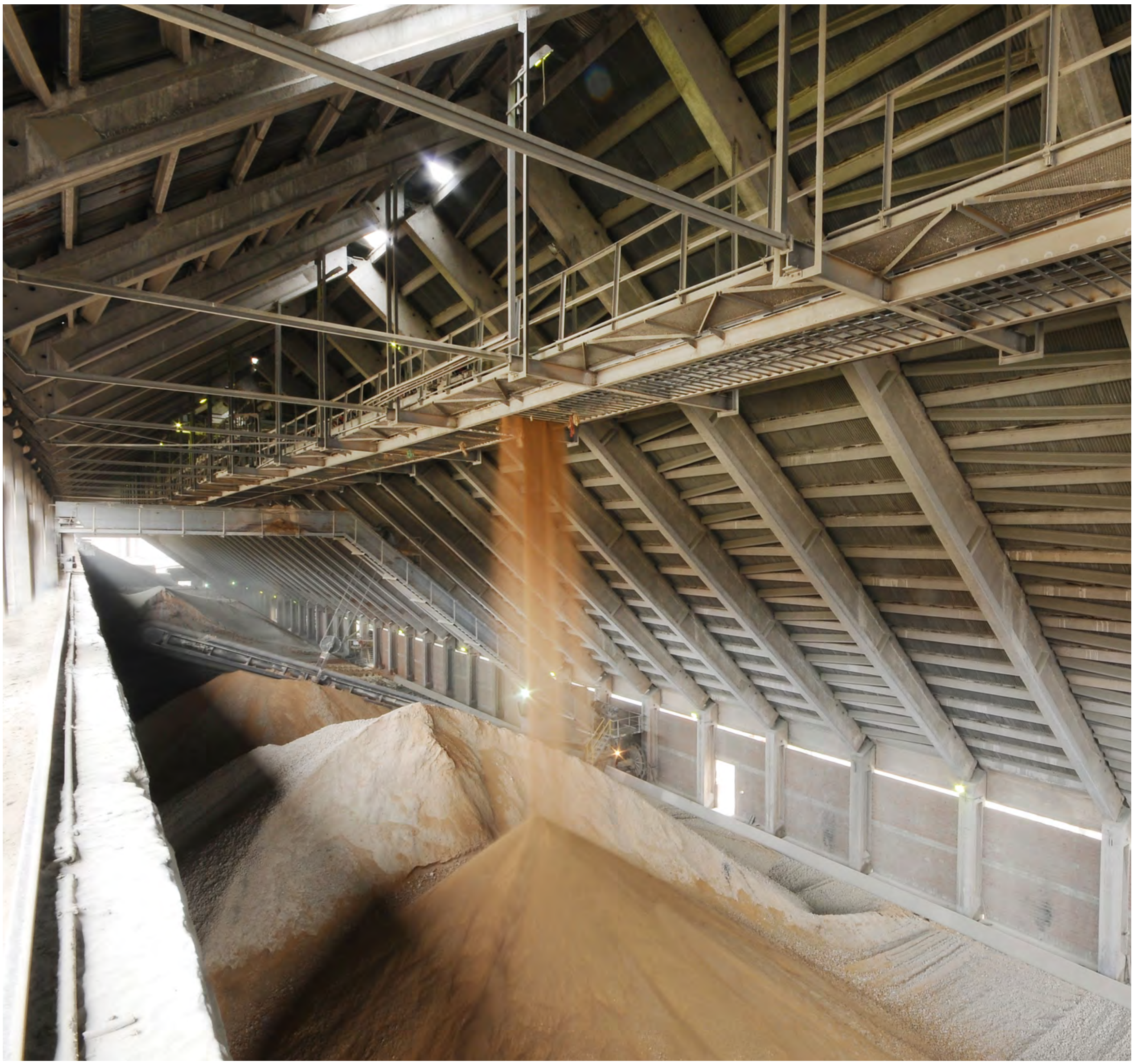
AVAILABILITY OF SCMs

	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

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:

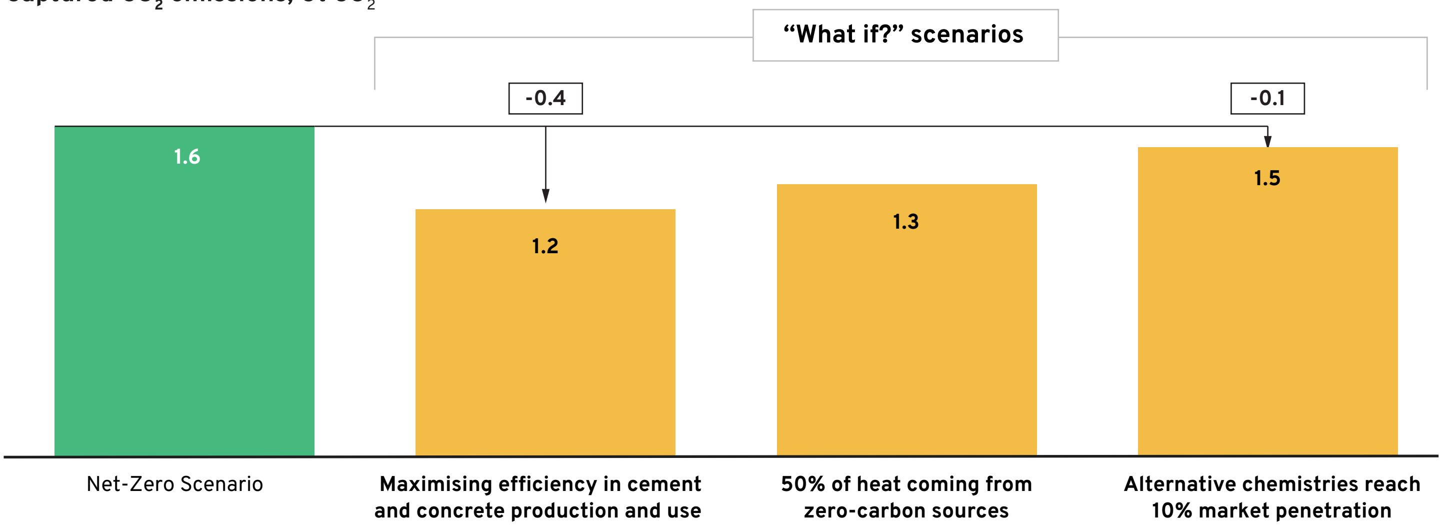
- If **new capture technologies** attain commercial deployment, they could reduce carbon capture costs through increased energy efficiency, reduced capital expenditures, and improved CO_2 capture efficiency and purity. Some of these technologies are in development (e.g., calcium looping, with a TRL of 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.

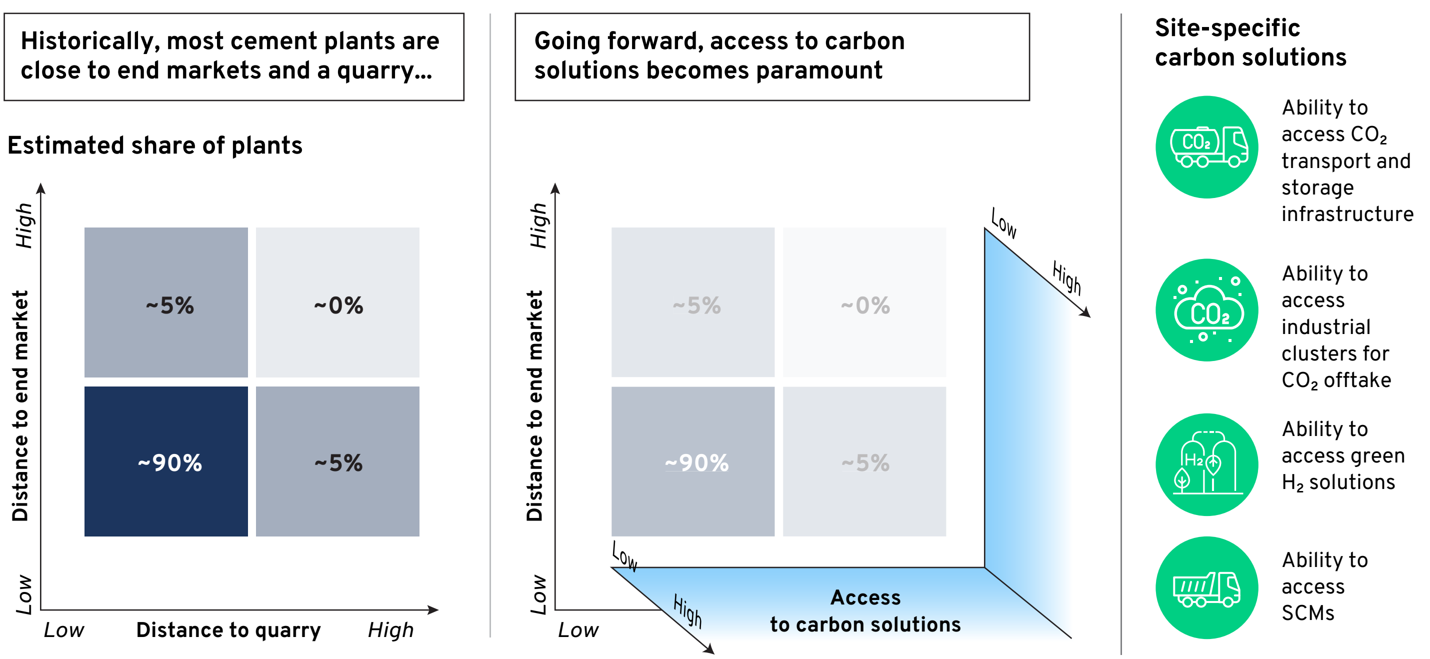
B. **Access to low-carbon energy sources,** including cheap renewable electricity or alternative fuels to heat the kilns (e.g., waste or low-carbon hydrogen).

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.

B. 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.

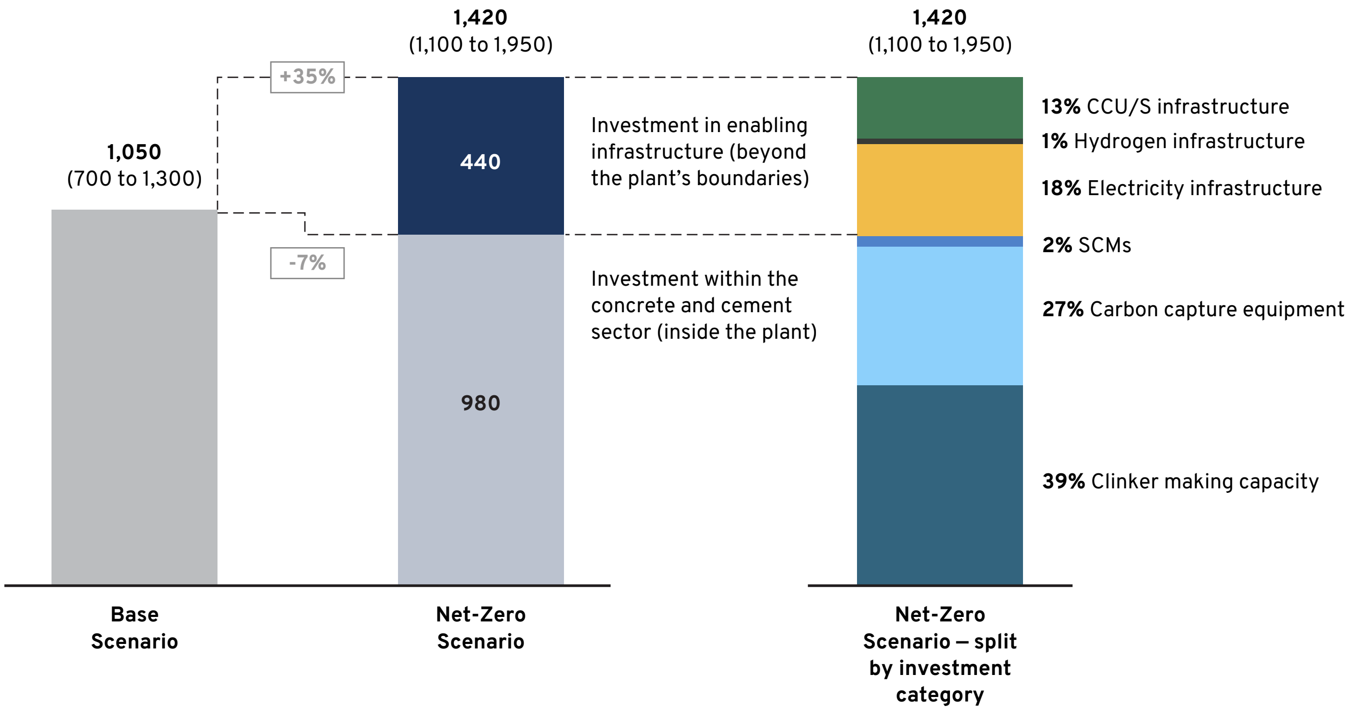
The pace of deployment of **emerging and breakthrough technologies** could impact the investment needs and operational costs of the sector. For example, alternative chemistries require new production facilities supported by increased low-carbon electricity use, which changes the investment needs in the 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

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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.