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GreenSpace Tech
by Deloitte

The road to net-zero is paved with decarbonized concrete

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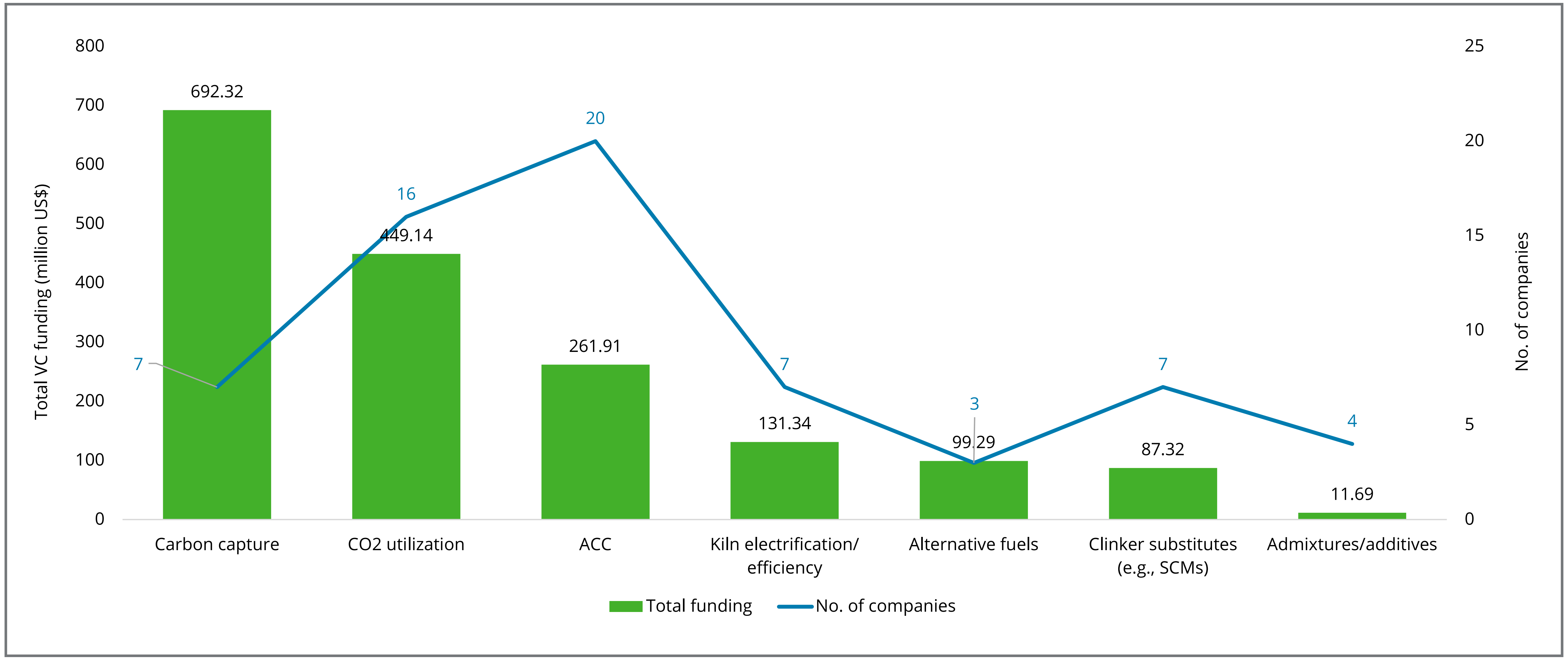
Concrete's net-zero challenge

Concrete is the most used manmade material on earth.[1] It's also a significant source of human-generated carbon dioxide (CO2) emissions—accounting for about 7% of global emissions.[2] Many cement and concrete suppliers have already taken steps to reduce their emissions by increasing energy efficiency of kilns and other equipment and using supplementary cementitious materials (SCMs) and lower-carbon alternative fuels.[3] However, even with the adoption of all three of these methods, a cement plant may reduce emissions by only 50%–60%.[4] To fully decarbonize, cement and concrete manufacturers will likely need other solutions. A new raft of solutions is emerging, each with its own trade-offs.

Next-generation decarbonization solutions for concrete production fall into two primary categories: carbon capture, utilization, and storage (CCUS); and alternative cement chemistries (ACC). CCUS solutions capture CO2 emissions from both fossil fuel combustion for energy and process emissions that result from the chemical conversion of calcium carbonate in limestone to calcium oxide. The CO2 can then be permanently sequestered either in the cement or concrete itself or in geologic reservoirs.[5] ACCs produce substitutes for ordinary portland cement (OPC), the most common cement used to bind conventional concrete.[6] They involve different materials or processes to produce lower-carbon cement. Abatement potential varies among CCUS and ACC solutions, but some can reduce emissions by as much as 90% or even result in net-negative emissions from concrete production. Though more expensive than more prevalent solutions mentioned above, costs are expected to decline with new innovations and economies of scale.[7]

Dozens of startup companies are working on CCUS and ACCs (see Figure 1). Combined, they account for more than two-thirds of lower-carbon concrete startups and US$954 million out of US$1.7 billion in funding raised since 2018, based on a Deloitte GreenSpace analysis for this publication. This report details commercial trends, opportunities, and challenges related to these technologies, as well as their potential to help the sector decarbonize.

Figure 1. Venture capital funding for green concrete startups (2018–2023) broken down by solution category.



Source: Deloitte analysis of CB Insights data pulled on 09/07/23.

Carbon capture, utilization and storage (CCUS)

CCUS is expected to be the biggest driver of emissions reductions in the concrete value chain by 2050, per sector net–zero roadmaps from the International Energy Agency (IEA), Global Cement and Concrete Association (GCCA), and CEMBUREAU, the European cement industry association.[8] Net abatement potential for carbon capture in cement manufacturing can be as high as 90%, assuming all captured emissions are permanently stored (see Table 1).[9]

Table 1. Example carbon capture solutions overview

Decarbonization solution (technology readiness level of 1–11 for cement/concrete)	Description	Projected costs in US$ (for implementation circa 2030)	Net emissions reduction
Post-combustion capture with amine-based solution (9)	The most mature carbon capture method, amine-based solvents trap CO2 molecules from flue gases, and then release them when reheated for capture and storage. Innovations are needed to help lower energy intensity and costs for this process.	Operational costs: up to $50/ton of clinker Capital investment required: • $200–275 million	84%
Oxy-fuel combustion capture (6)	Involves combustion of pure oxygen to fire kilns, resulting in a high concentration of CO2 in the flue gas. This can lower operating costs but involves a great deal of upfront work and costs to modify kiln equipment, optimize heat recovery, and install new equipment like an air separation unit.	Operational costs: $21–26/ton of clinker Capital investment required: • $200–230 million for new installation • $260–290 million for retrofit	80%
Membrane separation (4–5)	Uses inorganic membranes that act as barriers with CO2 selectivity, allowing CO2 molecules to pass through so it can be captured for transport and storage, while keeping other flue gases trapped.	Operational costs: $30–40/ton of clinker Capital investment required: • $190–260 million	57%
Cryogenic capture (5–6)	Cools flue gases to CO2's condensation or desublimation point, converting CO2 molecules into liquid or solid form for transport and storage.	Operational costs: $29–42/ton of clinker Capital investment required: • $180–230 million	70%

Decarbonization solution (technology readiness level of 1–11 for cement/concrete)	Description	Projected costs in US$ (for implementation circa 2030)	Net emissions reduction
Calcium looping (with integrated calcination reactors) (6–7)	Uses lime as a sorbent in a reactor to capture CO2, thereby creating calcium silicate, which is then regenerated in a second reactor to create a pure CO2 gas stream for transport and storage.	Operational costs: $16/ton of clinker Capital investment required: • $300–425 million for new installation • $345–490 million for retrofit	90%
Indirect calcination (a.k.a. direct separation) (6–7)	Involves indirectly heating the limestone in clinker with a special calciner designed to separate the resulting process emissions directly from other flue gases.	Operational costs: $6–10/ton of clinker Capital investment required: • $220–290 million for new installation • $200–260 million for retrofit	54%

Sources: Deloitte and Cambridge Innovation Consulting Ltd. analysis. The European Cement Research Academy 2022 Technology Papers. The IEA Technology Roadmap: Low-Carbon Transition in the Cement Industry

Carbon capture and storage (CCS) has not been deployed yet at commercial scale at a cement plant. However, dozens of projects are under development around the world,[10] with some expected to reach commercial maturity by 2030.[11] Much of this early activity is concentrated in Europe. Legacy cement manufacturers there have already substantially reduced carbon intensity of their operations through solutions like alternative fuels, and now face the prospect of reduced free carbon emissions allowances under the European Union's emissions trading scheme in its proposed "Fit for 55" legislation.[12] Fewer allowances will likely push them to make deeper emissions cuts, potentially through CCUS, or raise prices to offset higher costs.

The first commercial scale CCS project, at HeidelbergCement's plant in Brevik, Norway, is expected to start capturing more than 400,000 tons of CO2 per year in 2024.[13] The project will use an amine-based post-combustion capture solution, one of the most mature types of carbon capture technology and one of the most common among cement projects under development today. Companies in energy and other industrial sectors have used post-combustion capture since the 1990s,[14] and some are acting as technology providers for cement projects, including Brevik.[15]

Though more mature, amine-based post-combustion tends to incur high operational costs, largely due to the energy required for reheating amine solvents to capture CO2 molecules. Recently enacted government incentives, such as the increased 45Q tax credit in the US Inflation Reduction Act and the United Kingdom's £20 billion (US$25 billion) in funding for domestic carbon-capture projects announced earlier this year,[16] could help offset some of those costs.

New carbon-capture technologies may have lower operating costs. Oxy-fuel combustion capture, currently being demonstrated at multiple European projects, may reduce operating costs by half compared to amine-based post-combustion capture.[17] Other capture technologies being evaluated include a space-saving, modular CycloneCC industrial carbon capture unit that Carbon Clean is scaling with CEMEX in Germany and the Metal Organic Frameworks sorbent that Svante has been testing with LafargeHolcim in Canada.[18] Innovative technologies are expected to lead to increased adoption of carbon capture in cement manufacturing with the share of cement emissions captured reaching 29% by 2050, according to the IEA.[19] Deloitte's analysis identified seven carbon capture startups that are targeting cement applications—often along with other applications in the energy and industrial sectors. None of the seven have advanced beyond the pilot stage, and the vast majority of the venture capital funding in cement carbon capture (more than US$657 million) has gone to two companies: Carbon Clean and Svante.

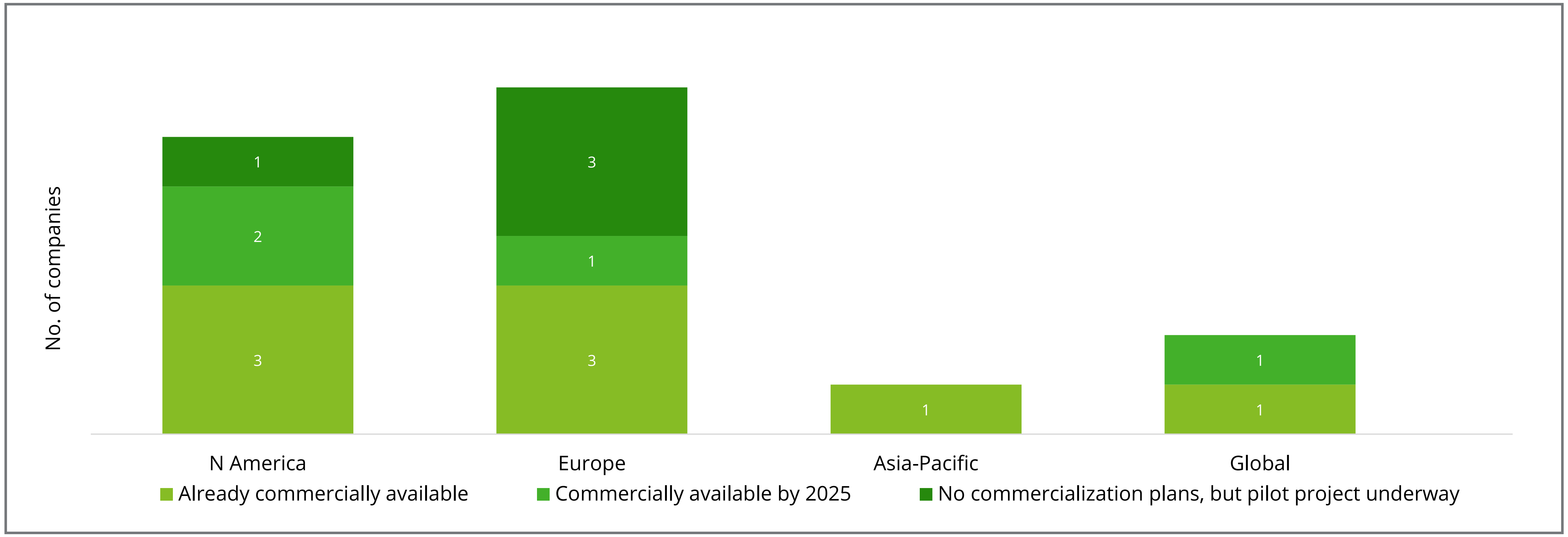
Utilization

Besides cost, another factor limiting the deployment of CCS in cement manufacture is the question of what to do with the captured CO2, which needs to be permanently sequestered to prevent leakage into the atmosphere. This is typically done in geologic formations or abandoned oil wells. But not all cement plants are close to geologic storage sites or CO2 pipeline infrastructure.

One way around this limitation is to sequester carbon in the concrete itself. Injecting CO2 into various stages of concrete production can trigger chemical reactions that transform the CO2 into solid minerals, such as calcium carbonate, thereby permanently sequestering it.[20] Leading methods include injecting CO2 into cement, supplementary cementitious materials, pre-cast concrete (i.e., concrete blocks), ready-mix concrete mixes (for on-site pouring), or even concrete waste byproducts. Deloitte has identified 16 startups working on carbon utilization in the cement production process, 12 of which have already commercialized offerings or plan to by 2025 (see Figure 2).

The different utilization methods present trade-offs. One intriguing method is CO2 mineralization of aggregate materials (e.g., sand, gravel, recycled concrete waste, or other filler materials that form concrete when mixed with cement and water). The mineralization of all aggregate materials in a concrete mix could sequester 20% more CO2 than generated in its production, storing up to 440 kg of CO2 per ton of material, and thereby creating concrete products with net-negative emissions.[21] However, high sequestration methods like mineralization tend to be energy intensive and expensive and can increase costs by up to 500% until scale economies bring costs down. Mineralized products are expected to make up less than 1% of the global aggregate market by 2030 and 10–18% by 2050.[22,23] In the meantime, lower-cost methods like carbon curing for pre-cast concrete, which costs only 27% more per ton than conventional methods and is expected to make up more than 75% of the global pre-cast concrete market by 2050, can be used as an alternative.[24] However, this method has a lower sequestration potential of only 1–8.5 kg of CO2 per ton of material.

Figure 2. Distribution of carbon utilization startups by commercial stage and region



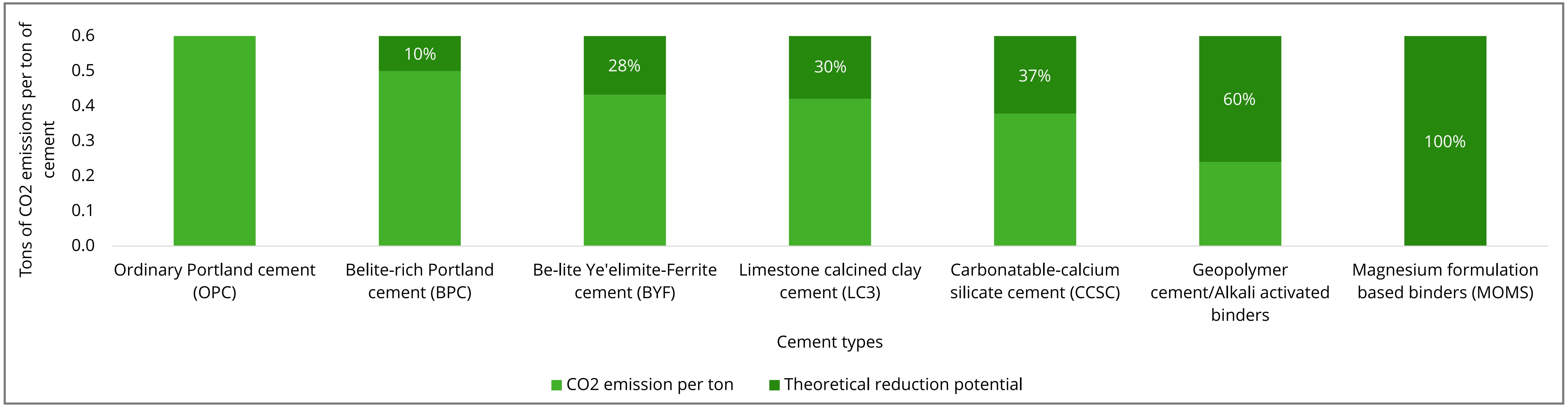
Source: Deloitte analysis of CB Insights data pulled on 7 September 2023. Note: "global" companies in the chart have commercial offerings in multiple regions.

Alternative cement chemistries

Some have hailed alternative cement chemistries (ACCs) as the key to decarbonizing concrete production, as they have the potential to replace ordinary portland cement (OPC) and eliminate its process and energy emissions.[25] Each ACC presents its own trade-offs (see Figure 3). Geopolymers, based on alumina silicates, can offer a lower carbon footprint but face limitations in terms of raw material availability and competition. Bio-based binding agents, or bio-cement, tend to have high abatement potential but are sometimes limited in their applications. Some, for instance, may corrode steel in reinforced concrete. Belite-rich portland and belite-ye'elimite-ferrite (BYF) cement can be produced in standard facilities but may face competition for raw materials.[26] Magnesium oxides can offer high abatement potential when made from magnesium silicate rocks, but this relies on new and unproven production processes.

According to Deloitte analysis, nine out of 20 ACC startups are on track to commercialize their offerings by 2025 (see Figure 4). One, for instance, has already introduced pre-cast concrete products based on its bio-cement technology and is piloting other applications like helicopter landing pads and offshore infrastructure.[27] Three of the top-funded ACC startups as of this writing, each having raised between US$45 million and US$80 million, are BioMason, Brimstone Energy, and Sublime Systems. Some legacy cement and concrete suppliers have been experimenting with ACCs as well.[28]

Figure 3. Emissions reduction potential of various OPC alternatives

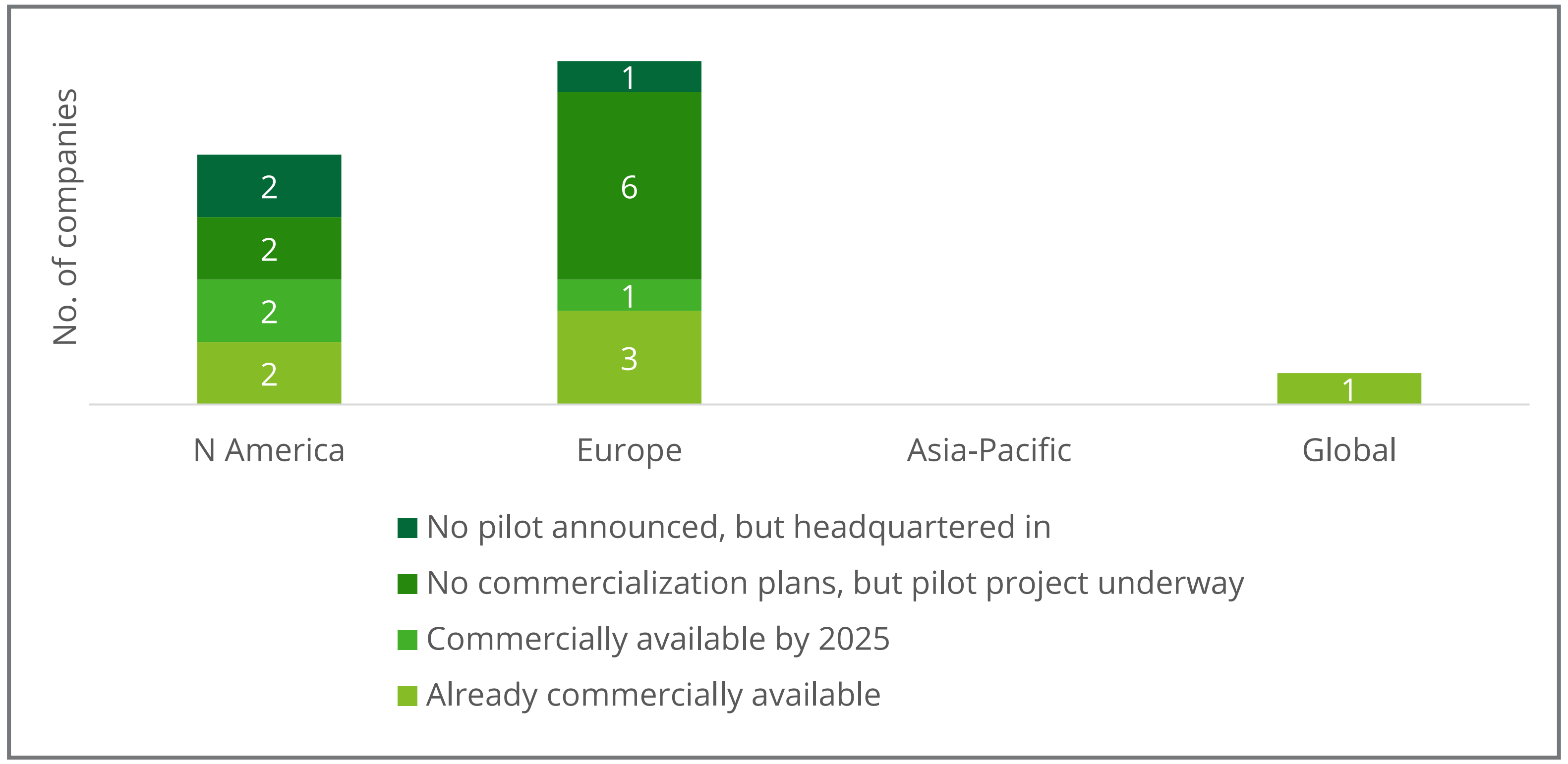


Note: All these cement types are at different levels of development stages, from MOMS being at the research stage, CSC and LC3 at advanced stages of development and BPC, BYF, and geopolymer cements used in some commercial applications today.
Source: Bringing low-carbon cement to market

Currently, ACCs are produced in small quantities and may face challenges gaining traction in the market. Legacy cement producers have been hesitant to explore alternatives to the ubiquitous OPC due to the abundance of its primary ingredient, limestone. Additionally, in some geographies, construction industry standards and building codes have yet to allow alternatives to OPC. Some, though, are considering updating standards to incorporate ACCs.[29]

The Global Cement and Concrete Association (GCCA) predicts that ACCs will make up just 5% of the global cement market by 2050.[30] However, even at this modest percentage, it could still translate to hundreds of millions of tons produced annually. Greater awareness of the benefits of ACCs could help accelerate adoption. For example, one maker of bio-cement says its products offer greater tensile strength and much lower thermal conductivity than OPC, resulting in greater durability, lower maintenance costs, and lower CO2 emissions related to heating and cooling buildings constructed with the material.[31]

Figure 4. Distribution of ACC startups by commercial stage and region



Source: Deloitte analysis of CB Insights data pulled on 7 September 2023

Chemistry and capture on the road to net-zero

Though still years from mainstream adoption, CCUS and ACCs are likely to play an important role in decarbonizing concrete. They both can address process emissions that cannot be addressed by renewables and electrification. Even if an OPC cement plant maximized use of other solutions like SCMs and zero-carbon fuels or electrified kilns, residual process emissions would still have to be captured and stored.

Scientific and commercial innovations in both CCUS and ACCs have brought the industry to a critical juncture for testing and piloting, creating partnership and investment opportunities along the concrete value chain.

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[5] The captured CO2 may also be sold to parties in other sectors for other utilization use cases, such as conversion to fuels (e.g., ethanol), minerals and chemicals, or direct use for food and beverages. However, Deloitte does not highlight such cases since the utilized CO2 will eventually be released into the atmosphere. In contrast, CO2 injection into cement/concrete results in virtually permanent CO2 sequestration.

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